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A
PRACTICAL TREATISE
ON
ELECTRIC LIGHTING.

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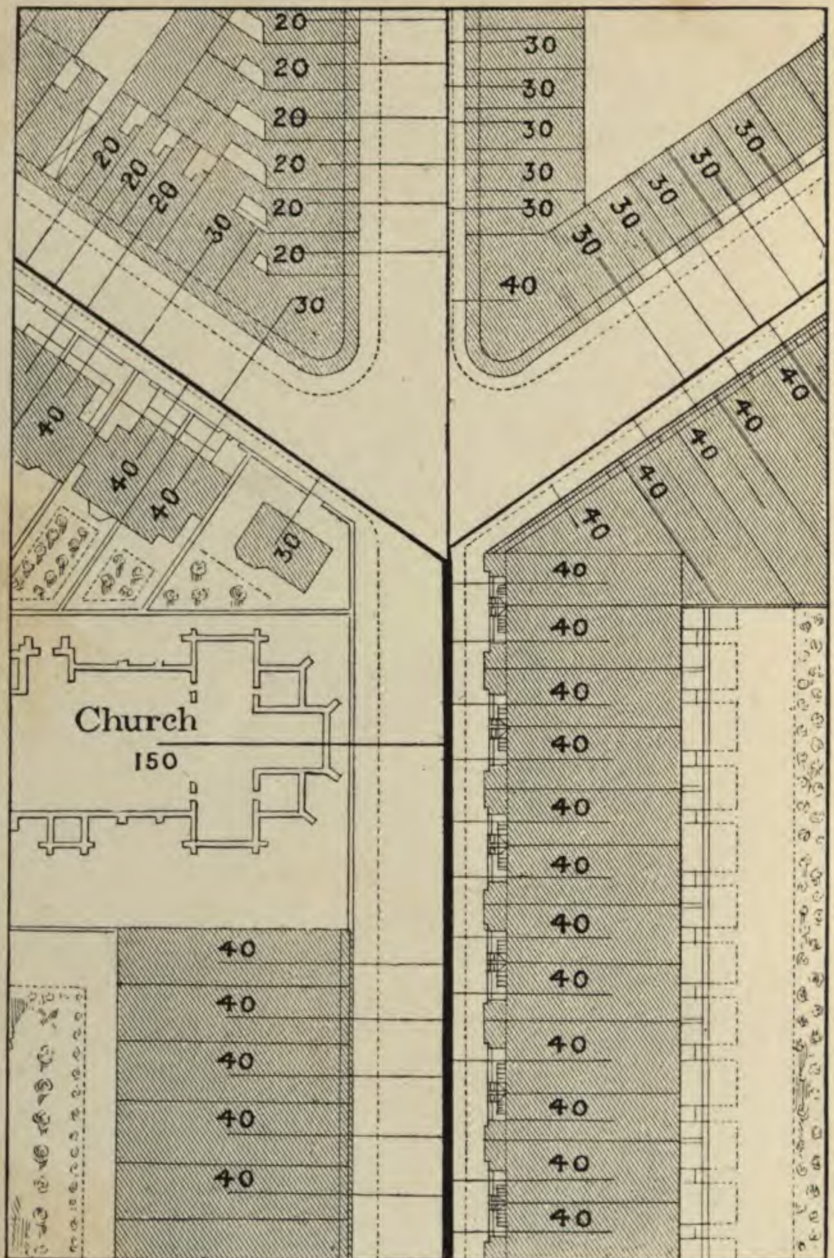

PLATE I.—MAP SHOWING STREET MAINS.

A

PRACTICAL TREATISE

ON

ELECTRIC LIGHTING

BY

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PREFACE.

WHEN the Paris Exhibition of 1881 first showed to the public the possibilities of electric lighting, it was assumed that in the course of a few months the electric light would be universally adopted. That assumption has proved to be unfounded, and the public have, speaking generally, gone into the opposite extreme, and declared that the electric light is a failure.

In October, 1881, I wrote in the *Quarterly Review*, "The day will come when gaslight will be as obsolete as wooden torches, and when in every house the incandescent lamp will have replaced the gas-jet."

In this, the darkest hour of electric lighting, when failure after failure has occurred, when company after company has become bankrupt, I unhesitatingly repeat this—I will not say opinion but—conviction, only adding to it my further conviction that the day of universal electric lighting is not even in the near future, but in the immediate future.

I reassert this conviction the more confidently because, having been myself one of those engaged in the study of electric lighting during the last three years of struggle and labour, I have seen not only the cause of past failures (failures already forgotten), but have further seen the steady growth of success, as invention after invention has stood the test, not only of experiment, but of months of careful trial.

The only cause of delay which I will here allude to is the delay in the *commencement* of public works, which has been undoubtedly caused by the action of the Board of Trade.

This delay, however much complained of by the public,

has been the salvation of electric lighting. If two years ago, as in the case of some American cities, our streets had been allowed to be opened for the purpose of laying electric-light wires by every speculator or inventor who thought, or wished the public to think, that he could supply electric light, it is certain that by now the number of accidents and failures which would have occurred would have ensured the enactment of restrictions far more stringent than any contained in the present law. The delay caused by the Board of Trade has been the delay not of the dilatory builder, but of the wise architect, who will not allow the building to be commenced till he has seen that the foundations are dug deep, and well filled with sound concrete.

This book has been in preparation for some two years, and has been modified again and again as the science of which it treats has progressed, in order that it might indicate the state of that science very nearly up to the present date.

In describing machines and lamps, I have not thought it necessary to describe many, but have selected those which are typical of different classes. Further, I have described but few things which, however useful they have been in the past, are not in my opinion likely to be useful in the future.

There is one point in the book itself to which I wish to allude: and that is the "method of calculating the horse-power wasted in street mains," described at page 26. It must be understood that the method there given is only what it professes to be—the method of *calculation*. I do not imply that the method of *arrangement* there given is the one which I recommend.

I have to thank Mr. Swan for much information as to the process of manufacture of his incandescent lamps, and for drawings illustrating it.

I have also to thank Mr. Crompton for accounts of his arc lamps, and for the chapter on "Carbons for Arc Lighting."

28, Collingham Place, London, S.W.
April 29th, 1884.

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A
PRACTICAL TREATISE
ON
ELECTRIC LIGHTING.

CHAPTER I.

INTRODUCTORY.

In all systems of artificial lighting of whatever kind, the light is produced by the incandescence or glowing of solid particles of matter. The heat required to produce this incandescence is produced in various ways. Our ordinary coal-gas consists of a combustible gas, richly charged with very small solid particles of carbon, which being made white hot by the combustion of the gas, glow and produce the light required.

If these solid particles are removed, the combustion of the gas produces no light. If, for instance, we mix with the gas a sufficient quantity of air to oxidise and consume the carbon particles, we obtain a flame hotter than the ordinary gas flame, but giving no light at all. A burner contrived specially to mix the right proportion of air with coal-gas, and known as the "Bunsen burner," is much used for cooking, and for other purposes where heat without light is required.

Again, if we burn pure hydrogen gas we shall obtain a flame giving great heat, but no light, because the hydrogen does not contain any solid particles. If, however, we introduce a little spiral of fine platinum wire into the flame, the heat of combustion will make the wire white-hot, and it will glow and give light. If, instead of the thin platinum wire,

we use a thick one, it will only become perhaps just red-hot, and although the same quantity of heat is being used, for the same quantity of hydrogen is being burned, yet the wire gives very much less light than before.

If now, instead of allowing the hydrogen to burn in the air where the oxygen, with which it is combined, being diluted with nitrogen, is diffused over a considerable space, we supply it with pure oxygen, the heat produced is concentrated in a much smaller space, and the temperature of the flame is consequently much higher. If the mixed gases are supplied under pressure, the size of the flame is still further reduced, and it can be concentrated on a very small portion of the surface of any solid body against which it may be directed. When the "oxy-hydrogen jet" is directed against a cylinder of lime, it raises a portion of its surface to a very high temperature indeed, and the heated lime gives off an intense light. This arrangement is well known as the "Lime-light."

Now, in all these arrangments we get a certain definite quantity of heat from a given quantity of fuel consumed, and this amount is the same in whatever way the combustion takes place. The same total quantity of heat is produced by the combustion of a cubic foot of hydrogen, whether it burns with a large flame in air, or whether it burns in an oxy-hydrogen blow-pipe.

The amount of light, however, which is produced by the expenditure of a given quantity of gas, or by the production of a given quantity of heat, depends entirely on the way that heat is applied.

Let us consider, for instance, the heat produced by the combustion of a cubic foot of hydrogen burnt in ten minutes. This heat may be expended in boiling a certain quantity of water, in which case it produces no light at all; or it may be employed in heating a thick platinum wire to dull redness, in which case it produces a little light, or it may be used to heat a thin wire to whiteness, producing a considerable light; or finally, by means of the oxy-hydrogen jet, it may be employed in heating a piece of lime to intense whiteness, ace the lime-light.

We see, therefore, that to produce a light, we must heat a solid body to incandescence. To produce a given light with the smallest possible expenditure of heat (that is of fuel and cost) *we must concentrate our heat on a solid body of the smallest possible size, so that that may be raised to the highest possible temperature.*

Solid bodies can be rendered incandescent, and made to give light by heat produced otherwise than by combustion. In the old "Flint-mill," used by miners before the invention of the safety-lamp, heat was produced by means of the energy applied by the man who turned the handle and caused a flint and steel to be continually knocked together. The heat caused the incandescence of the particles of flint knocked off, and the stream of sparks gave a certain quantity of light.

Solid bodies can also be made hot by the passage of a current of electricity through them. It will be our object in this Treatise to discuss the various methods of producing by electricity a temperature in solid bodies sufficient to cause them to give light. We will then compare the temperatures to which the incandescent solids are brought by heat produced by combustion as in a gas-flame, and by heat produced by the combustion of coals in a steam-engine and converted into electricity in a dynamo machine, and then we shall be able to compare the relative heat-economies of the two systems of lighting. To determine the relative money-economies, we must further discuss the various expenses incidental to the two systems, such as interest on plant, attendance, loss in transmission, &c., and their relative convenience in use.

We shall commence by a discussion of the principles involved in the economic production of electrical energy, and its conversion into heat and light, and go on to a description of some of the best and most typical apparatus now in actual use for the purpose, omitting for the most part descriptions of machines and lamps which, whatever their merits in the past, are not likely to be much used in the future.

CHAPTER II.

ON THE CONVERSION OF ELECTRIC CURRENTS INTO HEAT.

(1.) * LET us suppose we have a long water-pipe of large bore, bent round so that its two ends dip into the same cistern at the same level, and let a force-pump be connected to one end. We see that by a very small power we can cause a stream of water to flow round it. The only force opposing the motion will be the friction of the water in the pipe. To overcome this friction, however, a certain quantity of heat has to be expended in the steam-engine working the force-pump, and, by the friction, the sides of the pipe and the water will be more or less heated.

(2.) If the pipe is of small bore then more work will have to be expended to send a given stream of water through the pipe, and the friction being greater the pipe will be more warmed.

(3.) We see, then, that the stream of water has given us a means of taking heat from the engine fire, and conveying it to a distance, namely, to every portion of the sides of the pipe.

(4.) As long as the pipe is of the same bore throughout, the friction will be the same at all parts, and the heating will be uniform all along the pipe. If, however, we were to cut our pipe at one place, and interpose a spiral of very fine tube, a great deal of friction would be concentrated at one spot, and instead of the heating being uniform all along the pipe, by far the greater portion of the total heating would take place

* Compare the numbered paragraphs with those having corresponding numbers on page 6.

in the spiral. Thus this arrangement of the stream has given us a means of taking heat from the engine fire, and conveying it to any one place we like at a distance; namely the place where we have put the spiral.

(5.) In both cases we have expended *mechanical work* in forcing a *current* of water through a pipe offering *resistance* to the flow, which pipe by its resistance has reconverted a portion of the current into heat. The distribution of the heat depends on the distribution of the resistance. When the resistance is evenly distributed all along the pipe the pipe is evenly warmed. When the greater portion of the resistance is concentrated at one spot the greater portion of the heat is produced at that spot.*

(6). We must particularly note that the heat used has been expended in forcing a current of water through a resistance, and not in producing the water itself; and that if a pipe could be made without friction, and thus offering no resistance to the flow, then that a stream of water, however strong, when once started would go on flowing round the pipe for ever without the expenditure of any work at all.†

There are a class of substances called "conductors," along which a current of electricity can be made to flow in the same way as our current of water round the pipe. Substances along which electricity will not flow are called insulators. No substances are quite perfect either way, the best conductors offer some resistance to the flow, and the best insulators allow a little electricity to pass through them; but for our present purpose the metals and carbon among solids, and intensely heated or highly rarefied air and gases may be classified as conductors, and all other solids, and air and gas at ordinary temperatures and pressures, may be called insulators. With the conducting and insulating powers of liquids we have at present nothing to do.

Conductors differ greatly among themselves in the facility

* For the purpose of this illustration we consider the heat to stay in that portion of the pipe in which it is produced, and not to be carried away by the water.

† Newton, Lex. I.

with which they conduct electricity. A platinum wire, for instance, offers between five and six times the resistance to the flow of electricity as a copper wire of the same length and diameter. Also the resistance of a given length of a given wire is greater when the wire is thinner, being inversely proportional to its cross section. With the same cross section it is directly proportional to the length.

(1.) * Let us now suppose that by means of a steam-engine turning an electric generator we are forcing a current of electricity through a long copper wire of large diameter. The only force opposing the flow will be the resistance of the wire. To overcome this a certain quantity of heat has to be expended in the steam-engine working the electric generator, and by the resistance, the wire will be more or less heated.

(2.) If the wire is of smaller diameter the resistance will be greater, more work will have to be expended to send a given current through it, and more heat will be produced in the wire.

The relative amounts of work expended and heat produced in sending a current of electricity through a thick and a thin wire of the same length and material are inversely proportional to the cross sections of the wires.

(3.) We see that the electric current has given us a means of taking heat from the steam-engine and conveying it to a distance, namely, to every portion of the wire.

(4.) As long as the wire is of the same diameter and of the same material throughout, the resistance will be the same in all parts, and the heating will be uniform all along the wire. If, however, we cut our copper wire at one place and interpose a spiral of very fine platinum wire, a great deal of resistance will be concentrated at one spot, and instead of the heating being uniform all along the wire, by far the greater portion of the total heating will take place in the spiral.

Thus this arrangement of the electric current has given us a means of taking heat from the engine-fire and conveying

* Compare the numbered paragraphs with those having corresponding numbers on page 4.

it to any one place we like at a distance, namely, the place where we have put the spiral.

(5.) In both cases we have expended *mechanical work* in forcing a *current* of electricity through a wire offering *resistance* to the flow; which wire, by its resistance, has reconverted a portion of the current into heat. The distribution of the heat depends on the distribution of the resistance. When the resistance is evenly distributed all along the wire, the wire is evenly warmed. When the greater portion of the resistance is concentrated at one spot, the greater portion of the heat is produced at that spot.

(6.) We must particularly note that the heat used has been expended in forcing a current of electricity through a resistance, and not in producing the electricity itself (whatever that may be); and that if a wire could be made offering no resistance, then a stream of electricity, however strong when once started, would go on flowing round the wire for ever without the expenditure of any work at all.

An electro-magnet consists of a bar of soft iron surrounded by a coil of copper wire. When an electric current is sent round the wire the iron bar becomes a magnet. The copper wire offers resistance to the flow and becomes heated, and therefore work has to be expended at the generator to keep up the flow.

In a permanent steel magnet, according to the theory of Ampère, the magnetism is produced by the continuous flowing of electric currents in channels of no resistance which surround the molecules.

We may therefore regard a permanent steel magnet as an electro-magnet surrounded by a wire of no resistance, in which the current having once been started by whatever process of magnetization has been adopted, continues to flow eternally without producing any heat or requiring any heat to maintain it.

When at the place where we wish to concentrate our heat, we place a body of sufficiently high resistance, and send a sufficiently strong current through it, we can make it so hot that it will *glow and give light*. This is the principle of all electric lamps of whatever kind.

We have stated on page 3 that for light to be economically produced, it is necessary to raise the body producing the light to the highest possible temperature; or, in other words, to concentrate the heat in a solid of the smallest possible size or with the smallest possible cooling surface.

Now let us take a platinum spiral such that a given current makes it just red hot. We get a very little light. If we take another spiral composed of half the length of wire, and whose wire has half the section, it will have the same resistance as the first, and the same current passing through it, will produce the same quantity of heat in it, and expend the same quantity of heat in the steam engine. The platinum having very much smaller cooling surface will be raised to a much higher temperature, and will become white hot and give a brilliant light.

If, the resistance being still kept constant, the surface be further reduced, the temperature will be still further raised, and the same amount of heat will produce a still more brilliant light. It appears then as if by making the wire still thinner we could produce as much light as we pleased from a given quantity of heat.

The practical reason why we cannot do this is that platinum and all other metals fuse at what, in electric lighting, is a comparatively low temperature. Platinum fuses at about 2000° C. Further, if heated in air, all known substances rapidly oxidise and burn away.

The problem, then, which has had to be solved in electric lighting has been to obtain a substance having a resistance of convenient magnitude which can be heated by the current and which is either indestructible by intense heat or if slowly destroyed is capable of easy and continuous renewal.

Carbon, either alone or in conjunction with heated air, satisfies these conditions in a great measure. It has never yet been fused, and though it slowly oxidises when heated in air, yet its destruction can be either guarded against or compensated for as is done respectively in the two great systems of electric lighting now in use, i.e. the incandescent and the arc system.

In the "Incandescent" lamps of Swan, Edison, Maxim,

Lane-Fox, &c., the resistance, used to convert the current into heat, is that of a very fine thread or wire of carbon which is brought to a state of intense incandescence by the passage of a current through it, and which is protected from oxidation by being hermetically enclosed in a glass globe from which all the air has been exhausted. These lamps last for many months at a time, if not too much heated.*

In the "arc" lamps the current is sent through two stout rods of carbon which touch each other end to end. As soon as the current is established the rods are separated a little way, and the current continues through the heated air, which is a partial conductor of high resistance. Great heat is produced, the "poles" of the carbon rods glow with an intense whiteness, and small particles of carbon becoming detached are heated in the air between, and form a luminous "arc" from one pole to the other which adds to the light.

In this class of lamps the carbons being thicker can be raised to a much higher temperature than the carbon threads of "incandescent" lamps, and consequently they give much more light for a given quantity of heat, and are so much the "more efficient."

The carbon rods slowly consume away, and therefore have to be fed forward by suitable machinery. In arc lamps the expense of the carbon rods has to be added to the cost of producing the current in estimating the total cost of the light. In our 6th and 7th chapters we shall describe various lamps, both "incandescent" and "arc," now in use, but as the lamps have to be constructed to use currents of certain strengths, and as each lamp is intended to convert a certain definite quantity of electric energy into heat it is necessary for electrical engineers to comprehend the methods by which electrical quantities are measured and the standards to which they are referred. We shall therefore devote our next three chapters to an account of the standards now in use, and the methods of measuring electrical quantities by means of them.

* If overheated even in a perfect vacuum the filaments are destroyed with more or less rapidity by some process analogous to mechanical disintegration—they are, as it were, shaken to pieces.

CHAPTER III.

ELECTRICAL UNITS AND THEIR RELATION TO EACH OTHER, AND TO THE HEAT AND WORK UNITS.

In order to force water through a pipe offering resistance to the flow, a certain pressure or "aqua-motive force" must be supplied by a force-pump or otherwise. Similarly, in order to force a current of electricity through a wire, a certain electric pressure or *electro-motive force* must be supplied by the generator. A small electro-motive force will force a small *current* through a given *resistance ;* a larger, a proportionately larger one.

Current.—Ampere.

The unit of electric current is called the *Ampère.* It is a unit of flow or of stream. We speak of an electric current of so many ampères in the same way as we might speak of a water current of so many gallons per minute.* A 20-candle Swan lamp, new pattern, takes a current of about ·7 ampère.

Pressure.—Volt.

The unit of electric pressure is called the *Volt.* It is analagous to steam-pressure or to head of water. We speak of an electric pressure of so many volts as we might speak of a steam-pressure of so many pounds to the square inch, or a head of water of so many feet. One Daniell's cell gives

* In the case of the water flow we have no one word to express the strength of the stream, but have to speak of quantity per time.

a pressure of nearly one volt. One 20-candle Swan lamp (new pattern) requires a pressure of about 100 volts.

Resistance.—Ohm.

We know that generally a pipe of small bore offers a greater resistance to a flow of water than one of large bore; but the relation between the resistances of different pipes follows extremely complicated laws. We know, for instance, that a pipe of 1 square inch bore offers more resistance than one of 2 square inches, but we cannot say that it offers exactly, or even approximately, twice the resistance.

Electric resistance, however, as we have already stated,* follows a very simple law. For a wire of a given substance it is directly proportional to the length, and inversely proportional to the cross section. Thus, if we double the length of a wire we double its resistance. If we double the section we halve its resistance. If we double the diameter we quadruple the section and reduce the resistance to one quarter. If we double the length and double the section the resistance remains unaltered.

The unit of electrical resistance is called the *Ohm*. It is defined as the resistance at a temperature of 0 C., of a column of mercury of one square millimetre section and of a certain length.

The value † of the ohm was determined in 1862, by a committee of the British Association; and the result of their determination is that the standard mercury column has a length of, as nearly as possible, 104 centimetres. This is the value which is at present in practical use. It may be called the B. A. Ohm.

Recent investigations have, however, shown that it is about 1 per cent. too low; and at the Congress of Electricians, which met in Paris on Sept. 15, 1881, an International Commission was appointed to re-determine it with all possible accuracy. Whatever value the Commission arrives at is to be called the "Paris Congress Ohm," and is to be

* Page 6.

† For the theory of the determination of the Ohm, see my "Electricity," 2nd edition, vol. i. p. 303.

adopted permanently, and is not to be again changed, even if a further re-determination should show that it is not perfectly accurate.

To get some idea of the magnitude of the ohm, we may note that a mile of No. 16 copper bell-wire has a resistance of about 14 ohms, while the Atlantic cable has a resistance of about 7600 ohms. The carbon thread of a 20-candle Swan incandescent lamp (new pattern) has, when hot, about 143 ohms resistance, while the resistance of the heated air in an electric arc varies from 6 ohms to 1 ohm.

UNIT OF QUANTITY.—COULOMB.

The unit of electrical quantity is called the *Coulomb,* and we can speak of a current as one that conveys so many Coulombs per second through the wire. A current of a strength of one ampère conveys one coulomb per second.

OHM'S LAW.

The three units, volt, ohm, ampère, are connected by what is known as *Ohm's law.*

Ohm's law states that the *current in any circuit is directly proportional to the electro-motive force, and inversely proportional to the resistance,* and the units are so chosen that when there is one ohm resistance in circuit an electro-motive force of one volt produces a current of one ampère.

We see then that two volts acting through one ohm would give two ampères, or one volt acting through two ohms would give ½ an ampère.

Ohm's law may thus be written,—

$$\text{Current in ampères} = \frac{\text{Electro-motive force in volts.}}{\text{Resistance in ohms.}}$$

This is commonly abbreviated into the form,—

$$C = \frac{E}{R} \quad . \quad . \quad . \quad . \quad (1)$$

This may also be written,—

$$E = C R \quad . \quad . \quad . \quad (2)$$

or,—

$$R = \frac{E}{C} \quad . \quad . \quad . \quad . \quad (3)$$

By the use of these formulæ we can solve problems such as the following, which occur daily in electric lighting.

(1.) A machine gives an electro-motive force of 60 volts. What current will it send through a resistance of 5 ohms?

We have from (1),—

$$C = \frac{60}{5} = 12 \text{ ampères.}$$

(2.) What electro-motive force must a machine have to send a current of 2 ampères through a resistance of 25 ohms?

We have from (2),—

$$E = 2 \times 25 = 50 \text{ volts.}$$

(3.) What is the resistance of a circuit when an electromotive force of 800 volts sends a current of 10 ampères through it?

We have from (3),—

$$R = \frac{800}{10} = 80 \text{ ohms.}$$

Units of Heat and Work, and their relation to the Electrical Units.

Energy and Horse-Power.

The rate at which Energy is being expended, as for instance in maintaining a current, is in England * commonly measured in "horse-power."

One horse-power is equal to 550 foot-pounds per second, i.e. can raise 550 lbs. 1 ft. per second, or 1 lb. 550 ft. or 10 lbs. 55 ft. in the same time.

When horse-power is being expended in sending a current through a resistance, the conductor offering the resistance is heated. The quantity of heat produced per minute is equal to the heat which must be expended per minute in maintaining the current.

The horse-power required to maintain a current is, other things being equal, proportional to the square of the current. Thus, if one H.P. could maintain one ampère

* In France it is measured in "Force des Chevaux."
1 H.P. = 1·0139 Force de Cheval.

through a given resistance, 4 H.P. would be required to maintain 2 ampères through the same resistance.

The heat produced in the conductor is proportional to the square of the current. Thus, 2 ampères will produce four times as much heat in a certain wire as one will.

The horse-power required to maintain a certain current through a resistance is proportional to the resistance, and the heat produced by the current is proportional to the resistance.

Corollary. The heat produced per unit of length in a wire, on which depends the temperature to which the wire will be raised, is proportional to the resistance per unit of length.

The horse-power required to maintain a certain current under a certain pressure, is proportional to the current multiplied by the pressure.

Calculations.

Relation between Horse-Power, Current, and Resistance.

One horse-power can maintain a current of one ampère through 746 ohms. Or one of two ampères through,—

$$\frac{1}{2^2} = \frac{1}{4}, \text{ of 746 ohms, \&c.}$$

This is expressed generally by saying that the horse-power required to maintain a current is $\frac{1}{746}$ part of the square of the current in ampères multiplied by the resistance in ohms. This is abbreviated as follows,—

$$\text{H.P.} = \frac{C^2 R}{746} \quad . \quad . \quad . \quad . \quad (4)^*$$

This may also be written,—

$$C^2 = \frac{746 \text{ H.P.}}{R} \quad . \quad . \quad . \quad . \quad (5)$$

* 1 F. de C. will maintain a current of 1 ampère through 736 ohms. Equation (4) becomes,—

$$\text{F. de C.} = \frac{C^2 R}{736}$$

And generally H.P. can be translated into F. de C. by substituting 736 746 in the formulæ.

or,—

$$R = \frac{746\ \text{H.P.}}{C^2} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Problem (1).

What horse-power is required to maintain a current of 10 ampères through a resistance of 6 ohms ?

We have from (4),—

$$\text{H.P.} = \frac{10 \times 10 \times 6}{746} = \frac{600}{746}$$

or a little less than $\frac{6}{7}$ of a horse-power.

(2.) What current can 16 H.P. maintain through a resistance of 64 ohms ?

We have from (5),—

$$C^2 = \frac{746 \times 16}{64} = 186{\cdot}5.$$

whence C = 13·65 ampères.

(3.) Through what resistance can 10 H.P. maintain a current of 2 ampères ?

We have from (6),—

$$R = \frac{746 \times 10}{2 \times 2} = 1865 \text{ Ohms.}$$

Relation between Horse-power, Current, and E.M.F.

Equation (4) shows us that,—

$$\text{H.P.} = \frac{C^2 R}{746} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Equation (3) shows us that,—

$$R = \frac{E}{C} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Inserting in (4) the value of R given by (3) we have,—

$$\text{H.P.} = \frac{\frac{C^2 E}{C}}{746} = \frac{E\,C}{746} \quad . \quad . \quad . \quad . \quad (7)$$

or the horse-power expended in sending a current through any resistance, constant or variable, is $\frac{1}{746}$ part of the cur-

rent in ampères multiplied by the electro-motive force in volts which is driving it.

Equation (7) may also be written,—

$$E = \frac{746 \text{ H.P.}}{C} \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

or,—

$$C = \frac{746 \text{ H.P.}}{E} \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

Problem (1).

How much heat will be developed in a circuit by a current of 18 ampères driven by an E.M.F. of 200 volts?

We have from (7),—

$$\text{H.P.} = \frac{18 \times 200}{746} = 4{\cdot}82 \text{ horse-power.}$$

(2.) What electro-motive force must be given to a machine in order that 5 H.P. may just maintain a current of 25 ampères in the circuit.

We have from (8),—

$$E = \frac{746 \times 5}{25} = 149{\cdot}2 \text{ volts.}$$

(3.) A machine has an E.M.F. of 60 volts, what current will be developed by 80 H.P.?

We have from (9),—

$$C = \frac{746 \times 80}{60} = 994 \text{ ampères.}$$

Relation between Horse-power Resistance and E.M.F.

Equation (7) gives us,—

$$\text{H.P} = \frac{E\,C}{746} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Equation (1) gives us,—

$$C = \frac{E}{R} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Substituting in (7) the value of C given by (1) we have,—

$$\text{H.P.} = \frac{E\frac{E}{R}}{746} = \frac{E^2}{746\,R} \quad . \quad . \quad . \quad (10)$$

This may also be written,—

$$E^2 = \text{H.P. } 746 \text{ R} \quad . \quad . \quad . \quad . \quad (11)$$

or,—

$$R = \frac{E^2}{746 \text{ H.P.}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

Problem (1).

What H.P. is expended by an E.M.F. of 99 volts working through a resistance of 140·5 ohms ?

We have from (10),—

$$\text{H.P.} = \frac{99 \times 99}{746 \times 140{\cdot}5} = {\cdot}0936.$$

(2.) What E.M.F. will be developed if $\frac{1}{10}$ of a horse-power is employed in sending a current through 30 ohms ?

We have from (11),—

$$E^2 = \frac{1}{10}\ 746 \times 30 = 2238.$$

$$\text{Whence } E = 47{\cdot}3 \text{ volts.}$$

(3.) What should be the resistance of a lamp in order that when placed on a machine of 65 volts E.M.F. $\frac{1}{6}$ of a horse-power may be expended in it ?

We have from (12),—

$$R = \frac{65 \times 65}{\frac{1}{6}\, 746} = 33{\cdot}9 \text{ ohms.}$$

Relation between Work, Quantity, and E.M.F.

If we have a supply of water under constant pressure, which we are using occasionally, say to drive a water engine, we can tell how many foot-pounds of energy we have used at the end of a week, if we know the pressure and the total quantity of water used.

Similarly, if we know the electro-motive force at which our electricity is supplied, and the total quantity of electricity which has passed through our circuits, we can calculate the total quantity of energy expended, or of heat produced in the resistance, however much that resistance may have been varied during the flow.

The relation is given by the equation,—

$$W = \cdot 737 \, E \, Q \quad . \quad . \quad . \quad . \quad (13)$$

Equation (13) can be derived from equation (7), when we remember that 1 ampère equals 1 coulomb per second, and 1 H.P. = 550 foot-pounds per second. The number of foot-pounds expended in sending a coulomb through the circuit, is therefore 550 times the number of H.P. expended in maintaining an ampère.

(7) thus becomes,—

$$W = \frac{550}{746} E \, Q = \cdot 737 \, E \, Q \quad . \quad . \quad (13)$$

Where W is the work expended or heat generated expressed in foot-pounds, E is the electro-motive force in volts, and Q is the total number of coulombs of electricity which has passed.*

The equation may also be written,—

$$Q = \frac{W}{\cdot 737 \, E} \quad . \quad . \quad . \quad . \quad (14)$$

or,—

$$E = \frac{W}{\cdot 737 \, Q} \quad . \quad . \quad . \quad . \quad (15)$$

Problem (1).

With a constant E.M.F. of 110 volts how much work is expended in sending 10,000 coulombs through a circuit of varying resistance?

We have from (13),—

$$W = \cdot 737 \times 110 \times 10{,}000 = 810{,}700 \text{ foot-pounds.}$$

(2.) How much electricity will 33,000 foot-pounds send through a circuit with an E.M.F. of 60 volts?

We have from (14),—

$$Q = \frac{33{,}000}{\cdot 737 \times 60} = 746 \text{ coulombs.}$$

(3.) What must be the E.M.F. in a circuit for 1474 foot-pounds to send 10 coulombs through it?

We have from (15),—

$$E = \frac{1474}{\cdot 737 \times 10} = 200 \text{ volts.}$$

---

* See page 12.

Summary of Formulæ.

The following is a summary of the various formulæ which we have explained:—

C	stands for	Current in ampères.
E	„	E.M.F. in volts.
R	„	Resistance in ohms.
Q	„	Quantity in coulombs.
H.P.	„	Rate of expenditure of work in horse-power.
W	„	Work in foot-pounds.

1 H.P. = 550 foot-pounds per second = 33,000 foot-pounds per minute.

Horse-power.

$H.P. = \frac{C^2 R}{746}$	(4)	page 14.
$= \frac{E\,C}{746}$	(7)	„ 15.
$= \frac{E^2}{746\,R}$	(10)	„ 16.

Work.

$W = {\cdot}737\,E\,Q$	(13)	„ 18.

Current.

$C = \frac{E}{R}$	(1)	„ 12.
$= \sqrt{\frac{746\,H.P.}{R}}$ *	(5)	„ 14.
$= \frac{746\,H.P.}{E}$	(9)	„ 16.

Electro-motive Force.

$E = C\,R$	(2)	„ 12.
$= \frac{746\,H.P.}{C}$	(8)	„ 16.
$= \sqrt{H.P. \cdot 746\,R}$	(11)	„ 17.
$= \frac{W}{{\cdot}737\,Q}$	(15)	„ 18.

Resistance.

$R = \frac{E}{C}$	(3)	„ 12.

---

* The symbol $\sqrt{\;}$ means "square root of" the quantity under it.

$$= \frac{746 \text{ H.P.}}{C^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (6) \text{ page } 15.$$

$$= \frac{E}{746 \text{ H.P.}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (12) \text{ ,, } 17.$$

QUANTITY.

$$Q = \frac{W}{\cdot 737 \, E} \quad . \quad . \quad . \quad . \quad . \quad . \quad (14) \text{ ,, } 18.$$

THE COMMERCIAL ELECTRICAL UNIT.—DEFINITION.

The unit of electrical supply is defined by the Board of Trade in the Provisional Orders to be 1000 *ampères flowing for one hour under a pressure of one volt.*

This is the same as 100 ampères under a pressure of 10 volts, or of 10 ampères under a pressure of 100 volts, or generally as 1000 volt-ampères.

VALUE IN HORSE-POWER PER HOUR.

This unit is mathematically equal to 1·34 actual horse-power working for one hour, i.e. just over $1\frac{1}{3}$ horse-power working for one hour.

For we have by the formula (7), page 15,—

$$\text{H.P.} = \frac{E\,C}{746}$$

and where

$$E\,C = 1000$$

$$\text{H.P.} = \frac{1000}{746} = 1{\cdot}34 \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

VALUE IN 21-CANDLE SWAN LAMPS PER HOUR.

A Swan lamp as at present constructed takes exactly $\frac{1}{10}$th horse-power when working at 21 candles. Hence the commercial unit is a quantity of electricity that will feed 13·4 Swan lamps, each of 21-candle power for one hour.

VALUE IN 14-CANDLE SWAN LAMPS PER HOUR.

When lamps of smaller candle-power are used, one unit of electricity will feed a proportionably larger number of them.

One commercial unit of electricity will feed $\frac{21}{14} \times 13{\cdot}4$ equal to 20 14-candle Swan lamps for one hour.

Equivalent in Gas.

5 cubic feet of gas will feed one burner of about 14 candles for one hour, 100 cubic feet of gas will feed 20 14-candle burners for one hour;

Hence

One commercial electrical unit (when feeding Swan lamps) is approximately equal in illuminating power to 100 cubic feet of gas,

Or,

Ten commercial electrical units (when feeding Swan lamps) are approximately equal in illuminating power to 1000 cubic feet of gas . . . . (17)

Rule for Comparison of Prices.

We see from the above that to compare the price of electricity with that of gas we must multiply the price per electrical unit by 10, and the result will be the price of a quantity of electricity approximately equal in illuminating power to 1000 cubic feet of gas.

CHAPTER IV.

Rules for the Resistances of Divided Circuits.

In incandescent electric lighting the lamps are placed so that the currents leaving the mains divide between them. A knowledge of the right way to calculate the resistance of divided circuits is essential to electrical engineers.

When an electric circuit consists of two or more branches as in *b*, *c*, fig. 1, *the current divides between them in the inverse ratio of their resistances.* For instance, if the branch *b* has twice the resistance of *c*, then $\frac{2}{3}$ of the current passes through *c* and $\frac{1}{3}$ through *b*.

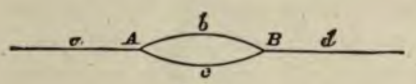


Fig. 1.

When wires are placed side by side, as *b*, *c*, fig. 1, so that the current divides between them, they are said to be "in parallel circuit," or "in multiple arc," or "in quantity;" all three expressions are used.

Fig. 2.

When they are arranged end to end, as in fig. 2, they are said to be "in series."

We see that in the "Quantity" arrangement the total resistance of the divided circuit is less than that of either of its branches, for the two wires side by side are equivalent to one whose cross-section is equal to the sum of the cross-sections of the branches.

If the resistances of all the branches are equal, the total

resistance of the whole circuit is the resistance of one branch divided by the number of branches . . . . . (18)

Problem :—

If we have 20 incandescent lamps connected in quantity (fig. 3), and each has a resistance of 125 ohms, what is their total resistance ?

We have from (18),—

$$R = \frac{125}{20} = 6 \cdot 25 \text{ ohms.}$$

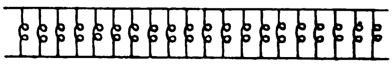


Fig. 3.

If the lamps are connected in series, their total resistance is the resistance of one multiplied by the number in series . . . . (19)

Problem :—

If we have 3 of the same lamps connected in series (fig. 4) what is their total resistance ?

We have from (19),—

$$R = 125 \times 3 = 375 \text{ ohms.}$$

Fig. 4.

We sometimes have to arrange a number of equal resistances, such as incandescent lamps, partly in quantity, partly in series, i.e. each branch of our parallel circuit is made up of two or more resistances in series.

The total resistance R of the circuit is then given by the following formula, where r is the resistance of one lamp, s the number of lamps in series in each branch, and q the number of branches arranged in quantity.

$$R = \frac{r\,s}{q} \qquad (20)$$

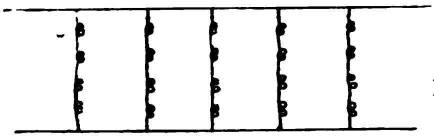
Problem :—

What is the resistance of 20 lamps of 25 ohms each, arranged in 5 branches, each consisting of 4 lamps in series (fig. 5) ?

We have,—

$$r = 25 \text{ ohms.} \quad s = 4. \quad q = 5.$$

And we have from (20),—



$$R = \frac{25 \times 4}{5} = 20 \text{ ohms.}$$

Fig. 5.

When the different branches have not all the same resistance, the formula for determining the total resistance is more complicated.

Let r_1, r_2, r_3, &c. (fig. 6), be the whole resistance of each of the branches respectively; each may be one resistance, or made up of several smaller ones in series.

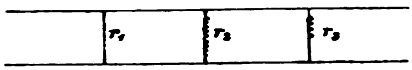


Fig. 6.

The total resistance R of the circuit is given by the formula.

$$R = \frac{r_1 \, r_2 \, r_3 \text{ \&c.}}{r_2 \, r_3 \text{ \&c.} + r_1 \, r_3 \text{ \&c.} + r_1 \, r_2 \text{ \&c.} + \text{\&c.}} \quad . \quad . \quad (21)^*$$

Problem :—

What is the resistance of a divided circuit of 5 branches, the total resistance of each branch respectively being 4, 12, 5, 100, and 3 ohms?

We have from (21),—

$$R = \frac{(4 \times 12 \times 5 \times 100 \times 3)}{(12 \times 5 \times 100 \times 3) + (4 \times 5 \times 100 \times 3) + (4 \times 12 \times 100 \times 3) + (4 \times 12 \times 5 \times 3) + (4 \times 12 \times 5 \times 100)}$$

$$= \frac{74{,}400}{18{,}600 + 6200 + 14{,}880 + 744 + 24{,}800} = 1{\cdot}14 \text{ ohm.}$$

It is often required to construct a resistance, such that a known fraction of the *whole* current shall go through one branch.

For instance, if we wish to measure a strong current by

* In this formula the numerator is the product of all the resistances, while each term of the denominator is the product of all except one, each one being omitted in turn. We also note that each term of the denominator consists of the numerator divided by the resistance which has been omitted in that term. This saves labour in the calculation.

a "galvanometer," * only constructed for the measurement of feeble currents, we may arrange it with a "shunt" as it is called, as in fig. 7, so that say $\frac{1}{10}$ of the current goes through the galvanometer *e* and $\frac{9}{10}$ through the shunt *b*. The galvanometer gives us the value of $\frac{1}{10}$ of the current, and 10 times this is the whole value of the current.

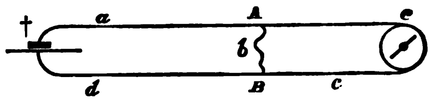


Fig. 7.

The general rule for the construction of shunts is the following :—

If it is desired to send $\frac{1}{n}$ of the current through any instrument, and the rest of it through the shunt, the resistance of the shunt must be,—

$$\frac{1}{n-1} \text{ of the resistance of the instrument} \ddagger \qquad (22)$$

Problem :—

We wish to measure a strong current by means of a galvanometer of 880 ohms resistance, and to send exactly $\frac{1}{100}$ part of the current through the galvanometer. What must be the resistance of the shunt which is to be placed in parallel circuit with the galvanometer ?

We have from (22),—

$$\text{Resistance of shunt} = \frac{1}{100-1} \text{ resistance of galvanometer}$$

$$= \frac{1}{99} \times 880 = 8{\cdot}88 \text{ ohms.}$$

(2.) What must be the resistance of the shunt for $\frac{1}{3}$ of the current to go through a lamp of 120 ohms ?

$$\text{Resistance of shunt} = \frac{1}{4-1} \times 120 = 40 \text{ ohms.}$$

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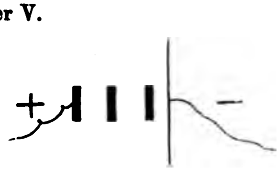
* See below, Chapter V.

† The symbol



indicates a battery, and is used with that meaning throughout this book.

‡ For the theory of this rule see my "Electricity," 2nd edition, vol. i. p. 276.

Self-adjustment of Current by Lamps in Quantity.

Suppose we have a generator of very small internal resistance and of constant E.M.F., and we supply a current from it to a number of lamps in quantity, the current in each lamp will be sensibly the same, whether the number of lamps connected is (within certain limits) great or small, i.e. if we have a number of lamps connected we can extinguish as many of them as we please without sensibly affecting the remainder.

For let E be the E.M.F. of the generator, g its internal resistance, r the resistance of one lamp, n the number of lamps. Thus, from (18) the total resistance of the are lamps will be $\frac{r}{n}$

and from (1) the total current will be

$$C = \frac{E}{\frac{r}{n} + g} = \frac{n\,E}{r + ng} \quad . \quad . \quad . \quad . \quad . \quad (23)$$

The current being divided between n lamps, the current c in each will be $\frac{1}{n}$ of the total current, i.e. will be

$$c = \frac{1}{n} \cdot \frac{n\,E}{r + ng} = \frac{E}{r + ng}.$$

We see that when g is very small, this is nearly independent of the value of n, i.e. is nearly the same whether many or few lamps are in the circuit.

This will be the case when g is the internal resistance of a battery with very large plates. With dynamo machines, however, the apparent resistance is so much increased by "self-induction" * that the self-adjustment only takes place over a very limited range, and other means of keeping the electro-motive force constant have to be used, which will be discussed in due course.

Method of calculating the H.P. wasted in a Network of Conductors supplying Lamps.

In all systems of electric lighting it is important to know what proportion of the electricity generated is utilized in

* See Chapter IX.

the lamps, and what proportion is wasted in heating the conductors.

When we have a rule for determining this we can properly apportion the diameter of each conductor to the current it has to carry, and to the distance to which it has to carry it; so that, on the one hand, we may not, by making the conductor too small, expend too great a quantity of coal in forcing the current through it; or, on the other hand, by making it too large, so increase our capital expenditure on copper that the interest on it is too large a proportion of the annual rental which we can charge for the electricity used in the lamps.

When the *same current* passes through two resistances, such, for instance, as a wire and the lamps fed by it, the horse-powers expended in the two resistances respectively, are simply proportional to the resistances. For by the formula (4), p. 14, if r and r' are the two resistances, the horse-powers expended by the *same current* C are

$$\text{H.P.} = \frac{C^2\, r}{746},$$

and

$$\text{H.P.}' = \frac{C^2 r'}{746},$$

and their ratios are

$$\frac{\text{H.P.}}{\text{H.P.}'} = \frac{\frac{C^2\, r}{746}}{\frac{C^2\, r'}{746}} = \frac{r}{r'} \quad . \quad . \quad . \quad . \quad (24)$$

When, as in arc-lighting, the lamps are all placed in series, the determination of the relative horse-powers is very simple, for the wire is of uniform section throughout, and its total resistance is its resistance per yard multiplied by its length in yards.

The resistance of each lamp is known, and the total lamp-resistance is the sum of these resistances.

Example. 16 arc lamps, each of 2·1 ohms resistance, are placed on a circuit 450 yards long, consisting of a wire having a resistance of ·006 ohms per yard. What proportion of the horse-power is used and wasted respectively?

The lamp-resistance $r = 16 \times 2{\cdot}1 = 33{\cdot}6$ ohms.

The wire-resistance $r' = 450 \times \cdot 006 = 2\cdot 7$ ohms.

The ratio

$$\frac{\text{H.P.}'}{\text{H.P.}} = \frac{r'}{r} = \frac{2\cdot 7}{33\cdot 6} = \cdot 08,$$

or 8 per cent.

Note.—We must be careful not to confuse the ratio of horse-power wasted to horse-power used, with the ratio of horse-power wasted to total horse-power.

The latter is the ratio of wasted horse-power to the sum of the wasted and used horse-powers; or,

$$\frac{\text{H.P.}'}{\text{H.P.} + \text{H.P.}'} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

This, in the case when the current is the same throughout the circuit, still depends only on the resistances, and is given by the formula

$$\frac{\text{H.P.}'}{\text{H.P.} + \text{H.P.}'} = \frac{r'}{r + r'} \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

With a circuit as given in the previous example, the ratio of the horse-power wasted to the total horse-power would be

$$\frac{2\cdot 7}{33\cdot 6 + 2\cdot 7} = \cdot 074, \text{ or } 7\cdot 4 \text{ per cent.}$$

With one group of incandescent lamps, either in quantity series, or of any combination of the two placed at the end of a pair of leads, as in fig. 8, the problem of the determination of the relative horse-powers wasted and used, is

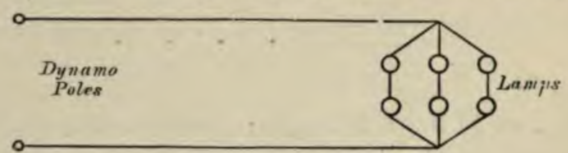


Fig. 8.

equally simple; for the wire being of uniform section, we know its resistance, and the resistance of the group of lamps is given by the formula (20) of page (23).

The current in every part of the leads being the same as the current in the group of lamps, the relative horse-powers are still proportional to the relative resistances.

We see in all these problems that the longer the conductor is, the thicker it must be, for if a given conductor wastes a certain horse-power, and we wish to double its length, i.e. *to put the lamps twice as far from the machine, without*

*increasing the waste, we must also double its sectional area, so as to keep its resistance constant, that is, we must quadruple its weight.**

In practical incandescent lighting, however, the lamps are distributed at intervals along the pair of conductors as in fig. 9, and the problem at once becomes much more

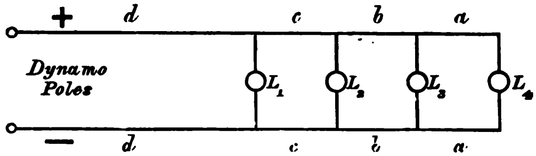


Fig. 9.

complex, because different parts of the conductors are carrying currents of different strengths, and the simple formula (25), page 28, is no longer applicable.

For we have in fig. 9

The portion	*a*	of the conductor	carries the current of	1 lamp.
„	*b*	„	„	2 lamps.
„	*c*	„	„	3 „
„	*d*	„	„	4 „

If we consider the conductors $+ \; d \; a$ and $- \; d \; a$ in fig. 9 to be the wires laid along a side street, then the branches L_1 L_2, &c., will not be single lamps, but may each be considered to represent the whole group of lamps in one house; while, if we consider the conductors to be the mains in a principal street, the branches L_1 L_2, &c., may be considered as representing the sub-mains branching into the side streets.

We see that L_1 L_2, &c., are not necessarily equal to one another.

In order to determine the relative horse-powers used and wasted in a system of town supply, I prefer to use a method which I communicated to the Society of Telegraph-Engineers on Dec. 13, 1883.

We first mark out on a large-scale map of the district the number of lamps likely to be required in each block or house.

We then draw the street-mains and branches radiating from the engine-house to the houses to be lighted.

We then, starting from the furthest points on each branch,

* See page 11.

work up towards the engine-house, marking on each branch and main the number of lamps it has to carry.

Plate I. is an example of a district so marked out; the plain numbers being the number of lamps* in the block or house on which they are marked, and the numbers surrounded by a circle being the number of lamps carried by the wire near which they are written.

To avoid confusion, the + conductor only is shown, and when the H.P. wasted in it has been obtained, the result must be doubled to obtain the total waste in the + and − conductors. Knowing the current used per lamp, we know the number of ampères which each wire has to carry.

We note that the "carrying" number in each branch is the sum of all the numbers beyond it, i.e. on the side furthest from the dynamo in that branch.

In order to secure the greatest economy of copper and of coals, the section of the conductor must be directly proportional to the current it has to carry, i.e. *as we leave the dynamo, the section of the conductor must diminish after each branch leaves it, in order that the same number of ampères per square inch may be carried by every part of the conductor throughout the system.*†

This condition being given, then, for a given district mapped out, the percentage of H.P. wasted in the conductors is simply proportional to the number of ampères per square inch which we use.

By the method we are about to explain, it is easy to calculate the percentage of horse-power wasted for any given number of ampères per square inch.

In order to find the ampères per square inch corresponding to the particular percentage horse-power that we are prepared to waste, we must assume some number of ampères arbi-

* The number of lamps need not be quite the total number erected, but should be the total number likely to be ordinarily in use. It is not necessary to provide copper to be always in position for lamps that are only lighted occasionally. In putting on extra lamps for short periods, care must however be taken that the heating limit is not approached. This will be discussed in the chapter on "Fire-risks."

† For the mathematical proof of this, see Appendix.

trarily, and find the actual horse-power wasted, and then the required number of ampères will bear the same ratio to the required horse-power that the arbitrarily-assumed number does to the horse-power corresponding to it . . (27)

For example:—

Suppose in a system where, say 100 H.P. is being used in lamps, we are prepared to waste $12\frac{1}{2}$ H.P., and that with an assumed current of 500 ampères per square inch we find (by the method of calculation which we are about to give) that we waste 16 H.P., then the right number of ampères per square inch for us to use is

$$\frac{12\frac{1}{2}}{16} \times 500 = 390 \text{ ampères per square inch.}$$

And if we have calculated the section of copper on the basis of 500 ampères per square inch, we must increase the section in the ratio of 16 to $12\frac{1}{2}$.

Calculation of H.P. wasted.

We now come to the method of calculating the horse-power wasted in a system of conductors, when a current of a certain number of ampères per square inch is flowing through it.

When there are the same number of ampères per square inch in a system, the *horse-power wasted in each cubic inch of copper is the same throughout the whole system or district.*

The resistance between the two faces of an inch cube of copper is ·0000007 (seven ten-millionths) of an ohm.

The horse-power (which we will call $\overline{\text{H.P.}}$) expended in a cubic inch of copper with a current of $\overline{\text{C}}$ ampères per cubic inch, is

$$\overline{\text{H.P.}} = \frac{\overline{\text{C}}^2 \times \cdot 0000007}{746} \quad . \quad . \quad . \quad . \quad . \quad (28)$$

With 500 ampères per square inch, the horse-power per cubic inch is

$$\overline{\text{H.P.}} = \frac{500^2 \times \cdot 0000007}{746} = \cdot 000234 \quad . \quad . \quad (29)$$

When we know this constant, $\overline{\text{H.P.}}$, and also the total number of cubic inches of copper in the district, we know the total horse-power wasted in the district.

To determine the number of cubic inches of copper in the district, we return to our map, on which the number of lamps on each branch is marked, and we calculate a constant for the area of copper per lamp corresponding to our assumed current of say 500 ampères per square inch.

For instance, if each lamp takes ·85 ampère, then for each lamp we must have

$$\frac{\cdot 85}{500} = \cdot 0017 = \text{square inch of copper.}$$

We then multiply the number of lamps on each section of the branch or main by this new constant, and we get the required area of this section, which we can mark upon it on the map.

We next multiply the area of each section by its length in inches, and this gives us its volume in cubic inches.

Adding all the results thus obtained together, we get the total number of cubic inches of copper in the positive leads throughout the district.

Twice this result is the total amount in the + and − leads together.

Multiplying this result by $\overline{\text{H.P.}}$, the horse-power constant (which, when $\overline{C} = 500$, is equal to ·000234), we get the total horse-power wasted in the copper in the whole system.

If the H.P. wasted is more or less than the desired amount, we, as we said before, alter $\overline{C}$ proportionately to the desired change in the H.P.

We of course know the H.P. expended in the lamps, as we know the number of lamps and the H.P. expended in each.

If H.P._L is the total H.P. used in the lamps, and H.P._W the total H.P. wasted, then the percentage P_W of the whole H.P. expended which is wasted in the leads, is

$$P_W = \frac{100\ \text{H.P.}_W}{\text{H.P.}_L + \text{H.P.}_W}.$$

As far as we have yet gone, we have assumed that all the lamps are alight whenever the current is flowing.

In practice this will not be the case, and we must note that if, the conductors remaining unchanged, we diminish

the number on every branch in a certain uniform ratio, we shall diminish the wasted H.P. *in the square of that ratio.*

That is, if, when 1000 lamps are burning, we are using 100 H.P. and wasting 10 H.P., then, if we reduce the number of lamps to 500, we shall reduce the used H.P. in the ratio of $\frac{500}{1000}$, i.e. to 50 H.P., but we shall reduce the wasted H.P. in the ratio of $(\frac{500}{1000})^2$, or to $\frac{1}{4}$ of its former amount, namely, to $2\frac{1}{2}$ H.P.

To put this in symbolical form, we may say that, with a given system of conductors, if

H.P._{WM} is the H.P. wasted when M lamps are burning,

and

H.P._{WN} „ „ N „ „

then

$$\text{H.P.}_{\text{WN}} = \left(\frac{\text{N}}{\text{M}}\right)^2 \text{H.P.}_{\text{WM}} \quad . \quad . \quad . \quad . \quad . \quad (30)$$

This formula is, as we said above, only correct when the number of lamps diminishes uniformly over the whole system, i.e. when an equal proportion of the lamps in every block are turned out simultaneously.

In districts containing the same class of houses, the condition is sufficiently nearly approximated to in practice to make the formula (30) a useful one in calculating probable waste. Assuming, then, this condition, we can, if we know the general average habits of the district as to the use of light, calculate the total relative quantities of coals which will be used in the engines in producing useful and wasted electricity respectively.

We will use the symbol H.P.H. for "horse-power-hour," i.e. for a H.P. working for an hour. Thus, 20 H.P. working for 3 hours would be equal to 60 H.P.H.

The coals used in an engine are practically proportional to the H.P.H., i.e. to the H.P. developed, multiplied by the hours during which the engine works. In order to determine the ratio of the coals used in producing wasted and useful electricity, we must take the H.P.H. used and wasted hour by hour throughout the night.

This will be best understood by an example.

Suppose that we have 1000 lamps and such a system of mains, that, when all the lamps are on, we use 100 H.P. and waste 10, and suppose that the number of lamps in use at the different parts of the night are as in the first two columns of the following table, then the H.P.H.s used and wasted will be as in the fifth and sixth columns respectively, where the letters L and W stand for "used in lamps" and "wasted" respectively.

Hours. P.M.	Lamps burning.	$H.P._L$	$H.P._W$	$H.P.H._L$	$H.P.H._W$
Before 5	Very few	Inappreciable			
5—6	100	10	·1	10	·1
6—7	500	50	2·5	50	2.5
7—10	1000	100	10·0	300	30·0
10—11	800	80	6·4	80	6·4
11—12	400	40	1·6	40	1·6
12—2 a.m.	200	20	·4	40	·8
After 2	Very few	Inappreciable			
	Total			520	41·4

Thus, although the percentage H.P. wasted when all the lamps are on is

$$P_w = 100 \frac{10}{100 + 10} = 9\text{·}9 \text{ per cent.,}$$

yet the percentage of coals wasted in the whole night is only

$$P_w = 100 \frac{41\text{·}4}{520 + 41\text{·}4} = 7\text{·}3 \text{ per cent.}$$

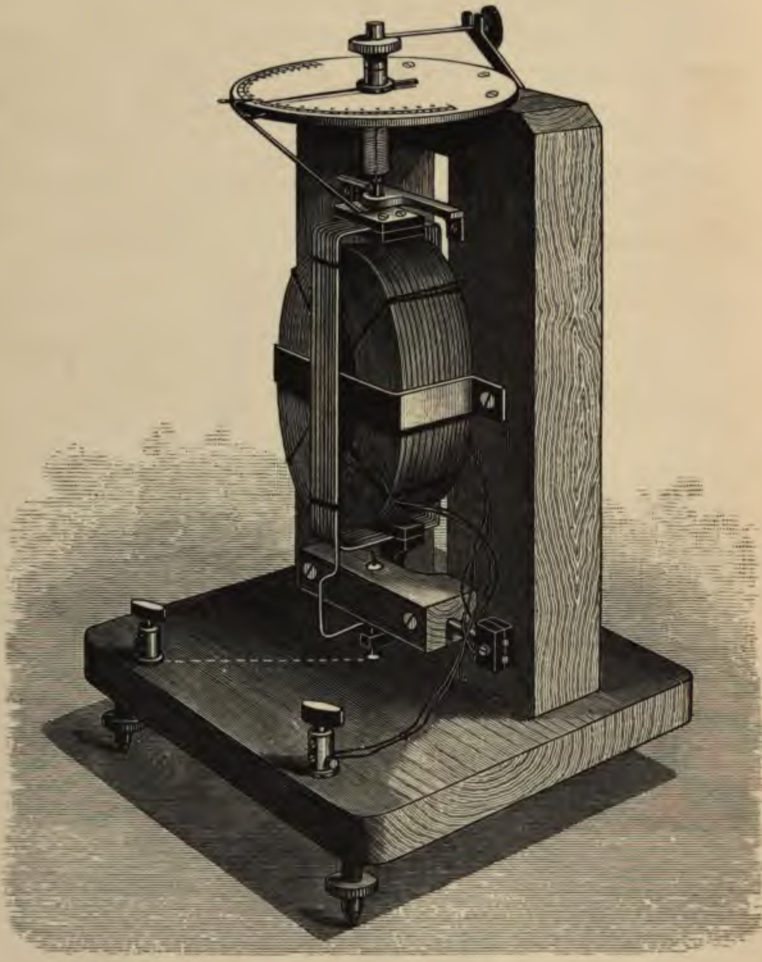


PLATE II.—THE SIEMENS ELECTRO-DYNAMOMETER.

CHAPTER V.

EXPERIMENTAL MEASUREMENT OF CURRENT—ELECTRO-MOTIVE FORCE—RESISTANCE—AND HORSE-POWER DEVELOPED IN RESISTANCE.

MEASUREMENT OF CURRENT BY THE SIEMENS ELECTRO-DYNAMOMETER. (Plate II.)

THE principle on which the electro-dynamometer is founded is the fact that two neighbouring wires carrying currents attract each other if the currents are in the same direction, and repel if they are in opposite directions.

The instrument as constructed by Messrs. Siemens consists of a fixed coil of wire (Plate II.) of the shape of a flattened ring, and a ring of one or more turns of stout wire suspended by a spiral spring. The plane of the suspended ring in its position of rest is at right angles to that of the fixed ring. The two ends of the suspended ring dip into mercury cups, which allow a current to be sent round it while it is still quite free to turn. The wires are connected so that a current entering the instrument passes through both the fixed and suspended coils.

The ring suspended by the spiral spring has its upper end attached to a nut or button called a "torsion head." The latter carries a pointer, which, when the torsion head is turned by hand, moves over a scale of degrees, and indicates through what angle the top end of the spring has been twisted.

When a current is sent through the instrument the sus-

pended coil is deflected, but is prevented moving more than about 5° by a stop. The torsion head is then turned by hand until the twist or torsion of the spring, acting against the current, brings the suspended ring back to its zero position. The number of degrees through which the torsion head has had to be turned is a measure of the strength of the current. A table is supplied with each instrument, showing the number of ampères corresponding to each degree of twist. The table is prepared by comparing the indications of each instrument with those of an absolute electro dynamometer,* when the same currents are sent through both instruments. Some of the instruments have two fixed coils, one consisting of a good many turns for feeble currents, the other of a few turns for strong currents. Such instruments of course have two reduction tables.

Thus to measure a current with this instrument, we first level the instrument carefully, and adjust it so that the suspended coil hangs at its zero position. If the instrument is in proper order, this will be when the torsion pointer is also at zero. We then send the current through it, and then turn the torsion head until the suspended coil returns to zero. We then look in the table to see what current corresponds to the reading of the torsion pointer.

It sometimes happens that owing to the instrument being a little out of order, the torsion head has to be turned a few degrees from zero, in order to bring the suspended coil to its zero when no current is passing. When this has to be done, the zero error must be subtracted from or added to the reading of the torsion needle, to give the amount of torsion balancing the current.

For instance, suppose when no current is passing, that in order to bring the coil to zero, the torsion needle has to be moved 4° in the same direction as that in which it is afterwards to be moved to balance the current; and that its position when the current is balanced is at the 20° mark.

Then, in order to balance the current, we have moved the torsion needle from 4° to 20°, that is through 16°, and our

* See my "Electricity." 2nd Edit. vol. ii. p. 79.

current will be that corresponding not to 20°, but to 16° in the table.

If we had previously had to move the torsion head 4° in the opposite direction and it balanced the current at 20°, we should have had to move it from − 4° to 20°, i.e. through 24°; and our current will be that corresponding to 24° in the table.

The chief advantage of the instrument is that it measures "alternating" currents as well as direct ones, for the attraction simply depends on the currents in the coils being in the same direction, and is not affected if they are both reversed. This is important, as a large class of the machines used in electric lighting give currents whose direction is reversed many times a second. It cannot, however, be regarded as an extremely accurate instrument, and is open to the great objection that each measurement takes some time, and that therefore it will give no information as to sudden or momentary variations of the current, such as take place when a lamp is out of order and the light is flickering.

Galvanometers.

If a wire be placed parallel to a magnetic needle, as in fig. 10, a current passing along the wire tends to set the magnetic needle at right angles to it. If the motion be opposed by some force such as the earth's magnetism, the effect of which on the needle gets greater as the deflection increases, the amount of deflection will depend on the strength of the current; and if the opposing force does not change, the same current will always produce the same deflection.

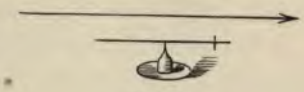


Fig. 10.

If the wire, instead of passing once over the needle, as in fig. 10, passes, say four times round it, as in fig. 11, the effect on the needle will be four times as great for the same current.

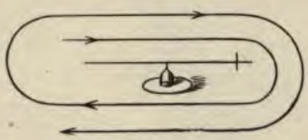


Fig. 11.

By properly proportioning the number of turns and the

force tending to bring the needle back to zero, we can construct a *Galvanometer*, as it is called, which will conveniently measure currents of any strength.

THE REFLECTING GALVANOMETER.

For the measurement of very feeble currents, Sir. Wm. Thomson's Reflecting Galvanometer (Plate III.) is used.

Its construction is as follows :—

Two coils of wire are used, round which the current goes in opposite directions. Magnets rigidly connected to each other are suspended in each. The similar poles of the magnets are turned in opposite directions. The directive action of the earth or of the setting magnet is thus very feeble, as it is only equal to the difference of the actions on the two magnets. The actions of the coils are added together.

The instrument is thus very sensitive.

THE LAMP, SCALE, AND MIRROR.

To detect and measure small angular deflections of a needle, a long pointer is necessary; but, if a long material pointer were attached to the needle, its weight would destroy the sensitiveness of the instrument.

Sir Wm. Thomson has therefore arranged a method by which a beam of light is made to act as a pointer of any length, and absolutely without weight.

A circular mirror, about $\frac{1}{3}$ of an inch in diameter, is rigidly attached to the needle.

Fig. 12.

A lamp and scale, of which the back (that is, the side furthest from the galvanometer) is shown in fig. 12, is placed on the table about two feet from the instrument. The light passes through a small opening in the lower part of the scale, falls on the mirror, and is reflected on to the upper part, making a spot of light. The least motion of the needle and mirror, of course, moves the spot along the scale. The distance which it moves is equal to that which would have

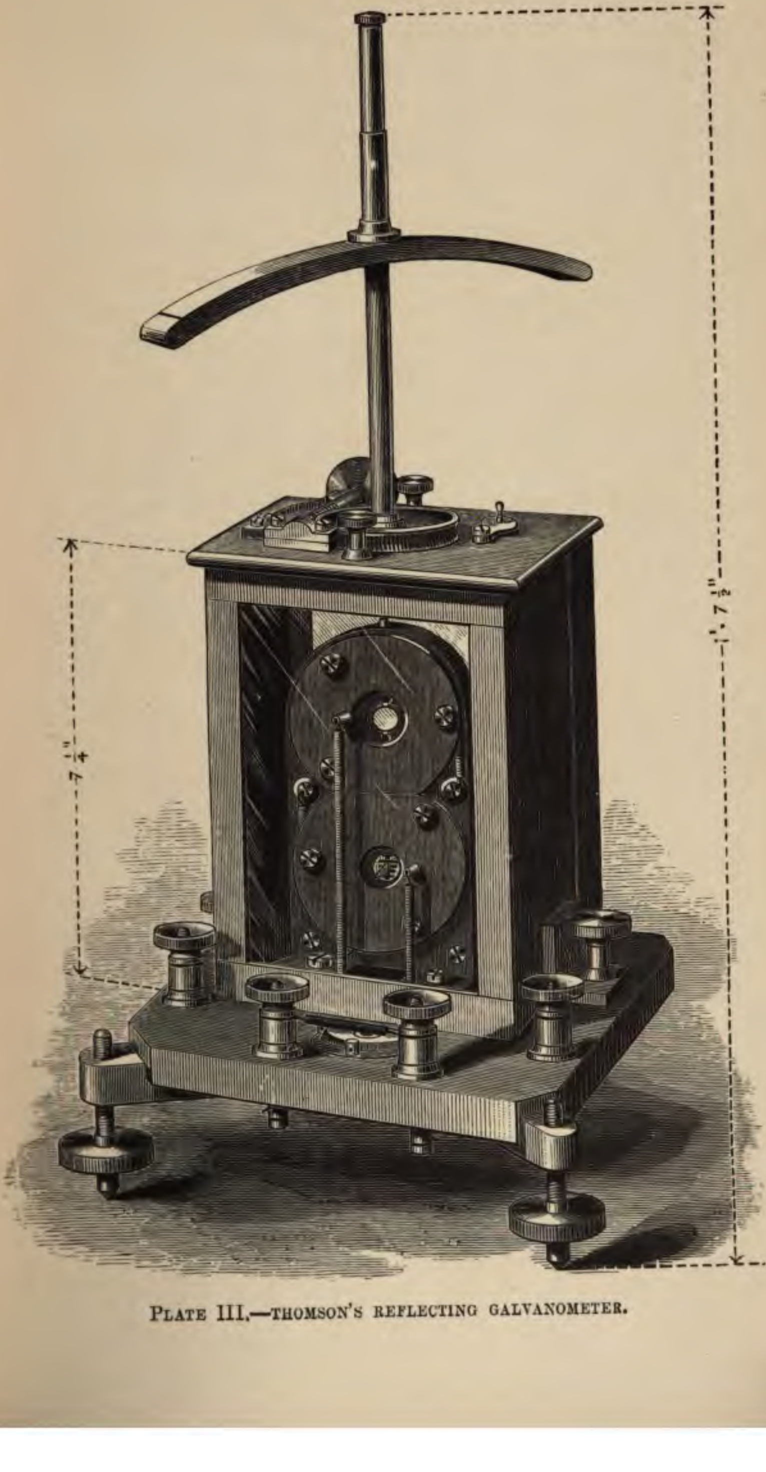


PLATE III.—THOMSON'S REFLECTING GALVANOMETER.

been traversed by the end of a pointer whose radius was double the distance from the mirror to the scale.

The aperture through which the light passes is sometimes a vertical slit, sometimes a round hole, with or without a a vertical wire stretched across it.

Sometimes the mirror is plane, and the light is brought to a focus on the scale by means of a lens. Sometimes the mirror is concave, and the lens is dispensed with.

When the slit is used, the moving image is a vertical line of light; when the hole is used, it is a bright disc crossed by a fine vertical black line, the image of the wire.

The scale is usually divided into millims., and printed black on white glazed paper.

In using a flat-wicked paraffin-lamp, the wick should be placed "edgeways"—that is, at right angles to the scale.

The position of the spot of light on the scale is adjusted to zero by the curved magnet seen at the top of Plate III.

It has a fine and coarse circular motion, and can be raised and lowered according as the instrument is required to be more or less sensitive.

GALVANOMETER SHUNTS.

In order to measure other than very feeble currents with these galvanometers, "shunts" are used with them, i.e. resistances so proportioned that either $\frac{1}{1000}$, $\frac{1}{100}$, $\frac{1}{10}$, or the whole current to be measured, can be sent through the galvanometer at will.*

Fig. 13 shows such a set. The wires bringing the current are attached to the two binding screws, and wires are also led from these screws to the terminals of the galvanometer.


Fig. 13.

When the plug is in the hole between the screws, no current passes through the galvanometer.† When it is in the hole marked $\frac{1}{999}$, then $\frac{1}{1000}$ of the whole current passes through the

* See page 24. Each galvanometer must have its own shunts; a set made for one instrument cannot be used with another.

† A plug should always be kept in this hole when the instrument is not in use.

galvanometer; when in $\frac{1}{99}$, $\frac{1}{100}$, and when in $\frac{1}{9}$, $\frac{1}{10}$ passes respectively; and when no plug is in, the whole current passes through the galvanometer. One plug only is used at one time.

THE TANGENT GALVANOMETER.

More powerful currents may be measured in absolute units by means of a "tangent galvanometer." The form of tangent galvanometer most suitable to this purpose consists of a single ring of wire (fig. 14) of large diameter, fixed so that it stands in a vertical plane, and having a small compass needle at its centre. To use the instrument it must be turned round till the zero of the scale is opposite the point of the needle, i.e. until the ring is in the magnetic meridian.


Fig. 14.

On the current being sent through the wire, the needle will be deflected. When we know the diameter of the ring and the strength of the earth's horizontal magnetic force, we can calculate the current from the *tangent* of the angle of deflection.

The tangent of an angle depends only on the angle, and will be found in books of mathematical tables, and in the appendix to this book.

If we assume that for England the earth horizontal force always has its present mean value at Greenwich,* we shall not introduce a greater error than others inseparable from the construction of a single ring galvanometer.

The current C in Ampères indicated by a deflection of δ degrees, when the ring of the galvanometer is D inches in diameter, will then be given by the following formula:—

$$C = \cdot 362\, D \tan \delta \quad . \quad . \quad . \quad . \quad . \quad . \quad (31)\dagger$$

* $H = \cdot 1794$.

† This is reduced from the formula given in my "Electricity," 2nd ed. vol. i. pp. 247 and 259, namely,

$$C = H \tan \delta \frac{a}{2\pi}$$

As D is the same for all experiments with the same galvanometer, it will save trouble if the value of ·362 D is calculated for each particular instrument, and marked upon it.

For instance, if the ring is 20 inches diameter, ·362 D = 7·24, and for that particular instrument the formula (31) becomes,—

$$C = 7{\cdot}24 \tan \delta.$$

Problem :—

What current is indicated by a deflection of 35° when the ring is one foot diameter? A reference to the tables gives us tan 35° = ·7002, and from (31) we have,—

$$C = {\cdot}362 \times 12 \times {\cdot}7002 = 3{\cdot}04 \text{ Ampères.}$$

If the ring has more than one turn of wire, the number of ampères given by the formula must be divided by the number of turns to give the true value of the current, or in other words the formula (31) becomes,—

$$C = \frac{{\cdot}362 \text{ D} \tan \delta}{n} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (32)$$

Where n is the number of turns.

Another method of graduating a tangent galvanometer requires a knowledge of the electro-motive force and internal resistance of the battery used to deflect it.

This method is not so accurate as the first, but is sometimes useful when the ring cannot be accurately measured.

The electro-motive force of a Grove's cell has a tolerably constant value of 1·93 volt.

The resistance is determined as follows :—

Let α be the deflection when only the battery and galvanometer are in circuit. The current is proportional to tan α.

Now let a small known resistance r be inserted. The deflection will be reduced to β, and the current is proportional to tan β.

where H is the earth's horizontal force in C.G.S. measure, a the radius of the ring in centimetres, and π the ratio of the circumference of a circle to its diameter = 3·1416.

The ratio of the two currents is,—

$$\frac{\tan \alpha}{\tan \beta}.$$

But the electro-motive forces being the same,* the ratio of the currents is the inverse ratio of the total resistances in circuit in the two cases.

Let x be the resistance of the battery, galvanometer, and connecting wires.

In the first case, when the deflection was α, x was the total resistance in circuit. In the second, where the deflection was β, the total resistance was $x + r$.

The ratio of the currents was therefore,—

$$\frac{x + r}{x}.$$

and we have,—

$$\frac{\tan \alpha}{\tan \beta} = \frac{x + r}{x}.$$

or,—

$$\tan \alpha . x = \tan \beta \, (x + r).$$

or,—

$$(\tan \alpha - \tan \beta) \, x = \tan \beta . r.$$

or,—

$$x = \frac{\tan \beta}{\tan \alpha - \tan \beta} r \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)$$

Having thus obtained the total resistance in circuit, we can calculate the value of the deflection in ampères, by removing the resistance r, and sending the current from several cells through the galvanometer and using the formula,—

$$C = \frac{n \, e}{x} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

Where n is the number of cells, and e the E.M.F. of one cell. For a Grove's cell $e = 1{\cdot}93$ volt, approximately.

Let δ be the deflection given by the now known current C.

We have,—

$$C = k \tan \delta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (35)$$

whence—

$$k = \frac{C}{\tan \delta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (36)$$

* The electro-motive force is apt to vary a little with change of resistance, and hence the method is not perfect.

k, being the constant of the galvanometer, the same quantity as the formula (32) gave equal to,—

$$\frac{\cdot 362\ \mathrm{D}}{n.}$$

Example.

Let us suppose we have a galvanometer given us to graduate, and that we use 4 Grove's cells.

We have first to obtain the resistance x (eq. 33) of the battery, galvanometer, and connecting wires.

Suppose the deflection to be 40° when the cells are connected direct to the galvanometer.

We have $\alpha = 40°$, and from the tables, $\tan \alpha = \cdot 83909$.

We now insert $\frac{1}{2}$ ohm resistance, the deflection will be reduced, say to 29°.

We have $\beta = 29°$, and from the tables, $\tan \beta = \cdot 55430$.

From (33) we have,—

$$x = \frac{\cdot 55430}{\cdot 83909 - \cdot 55430} \times \tfrac{1}{2} = 1\cdot 47 \text{ ohm}.$$

To find the constant of the galvanometer we have from (34),—

$$\mathrm{C} = \frac{4 \times 1\cdot 93}{1\cdot 47.}$$

when no extra resistance is inserted.

But we also found when no resistance was inserted, the deflection δ was 40°, and $\tan \delta = \cdot 83909$.

Hence we have using (36),—

$$k = \frac{4 \times 1\cdot 93}{\cdot 83909 \times 1\cdot 47} = 6\cdot 27.$$

And the formula (35) for this particular galvanometer becomes,—

$$\mathrm{C}\ (\text{in ampères}) = 6\cdot 27 \tan \delta.$$

If a galvanometer is much used, it is convenient to calculate the value of $k \tan \delta$ for each degree, and use the table so prepared, instead of making a fresh calculation for each experiment.

Currents exceeding 10 ampères may be measured by using a shunt (p. 25, fig. 7, and p. 39, fig. 13) and sending a known fraction of the current through the galvanometer.

Professors Ayrton and Perry's Instruments.

Professors Ayrton and Perry have devised a series of instruments specially adapted for making the electrical measurements required in electric lighting. The conditions which they have had in their minds in devising them have been the following :—

First, the instruments must be portable, must be moderately cheap, and easy to use.

Second, and this is most important, they must be "dead-beat"—i.e. changes in the quantity which is being measured must be instantly indicated by the needle without any oscillation.

Third, it must be easy to calibrate them, and to verify the calibration at any future time.

The Ammeter.

The instrument they use for the measurement of currents is called the *Ammeter*, or ampère-measurer, and is a special form of galvanometer. It is shown at about three-quarters its actual size in fig. 15.

The case of the instrument is composed of a powerful horseshoe magnet, inside which the needle moves on a vertical pivot. A pointer attached to the needle allows the deflection to be read on the scale on the top of the instrument. The horseshoe magnet so acts on the needle as to always tend to bring back the pointer to zero. It gives a constant magnetic field independent of changes in the earth's magnetism. The needle is deflected by a coil of wire consisting of ten rings surrounding it.

These rings are attached to springs which press on the roller seen on the right. When the roller is turned in one direction all the rings are connected in series, so that a current entering the instrument goes round them one after another, and so passes ten times round the needle. When the roller is turned in the other direction, marked "quantity," the wires are all connected laterally, so that they are equivalent to one very thick wire, and the current passes only once round the needle.

We see that with the "series" arrangement a given current has ten times the effect on the needle that it would have if the roller was turned to "quantity." We therefore use the series arrangement for measuring feeble currents, and the quantity arrangement for measuring strong ones.

The coils and the inside shape of the poles are so arranged that the deflection is proportional to the current.

The needle is deflected right or left according to the

Fig. 15.

direction of the current, and it can move through 45° in each direction.

The roller arrangement allows the instrument to be easily graduated by means of a few cells of a battery of known electro-motive force; as when the roller is placed in the "series" position the current of three or four cells produces a considerable deflection. Its indications may either be compared with those of a measured tangent galvanometer (eq. 32, page 41), or we may use the method of

graduating described on pages 41—43. The little plug in the front right-hand corner of fig. 15 short-circuits a resistance coil of one ohm—so that when the plug is removed one ohm resistance is added to the circuit.

To determine the resistance of the battery and galvanometer we use formula (33), only instead of tan α and tan β we use the deflections α and β themselves, as in this instrument the currents are proportional to the deflections and not to their tangents.

We also remember that $r = 1$.

The formula (33) then becomes

$$x = \frac{\beta}{\alpha - \beta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (37)$$

To obtain the value of the current we still use the formula—

$$C = \frac{n\, e}{x} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

while to calculate k, the constant of the instrument, (36) becomes

$$k = \frac{C}{\delta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (38)$$

and the formula for using the instrument is altered from (35) to

$$C = k\, \delta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (39)$$

Messrs. Ayrton and Perry now usually adjust their instruments so that $k = \frac{1}{5}$ when the roller is at series, and 2 when it is at quantity.

$k = \frac{1}{5}$, means that each degree is $\frac{1}{5}$ ampère, or that an ampère deflects 5° while $k = 2$ means that each degree is 2 ampères, or that an ampère deflects $\frac{1}{2}$°.

Problem :—

(1) With an instrument so adjusted, what current is indicated by a deflection of 15° when the roller is at series?

(39) gives us

$$C = \frac{1}{5} \times 15 = 3 \text{ ampères.}$$

(2) What current will the same deflection indicate when the roller is at quantity?

$$C = 2 \times 15 = 30 \text{ ampères.}$$

The instrument is absolutely dead-beat, and the shortest variation of the current is shown on it.

For instance, if a light dynamo machine is being driven by belting, the needle of the ammeter gives a little jump each time the lacing of the belt passes the pulley.

We see then that with the series arrangement we can measure currents up to 9 ampères, and with the quantity arrangement up to 90 ampères.

When used for measuring strong currents by the quantity arrangement, the wires are to be attached to the screws P P; for weak currents with the series arrangement, they are to be attached to S S. The instrument is so arranged that it is impossible to send a strong current through the series arrangements as long as P and S are not interchanged.

When the instrument is not in use, the poles of the magnet are connected by a soft iron armature. In order that the observer may not forget to take off the armature on commencing work, a brass cover for the dial may be conveniently fixed to the armature, so that the dial cannot be seen except when the armature is removed.

Sir Wm. Thomson's Graded Galvanometer (Fig. 16).

This is an absolute galvanometer, with a very wide range of usefulness, as the magnet and scale can be moved nearer or further from the coil, according to the strength of the current under examination. With a feeble current the magnet is placed close to the coil, and a good deflection is thus obtained, while with more powerful currents it is moved further off, and the deflection is still kept within the range of the instrument. Numbers are engraved on the scale along which the magnet-holder slides, which are used in calculating the value of the current corresponding to a given deflection.

The needle is brought to zero partly by the earth's force and partly by the curved magnet shown in fig. 16.

In adjusting the instrument, the magnet must be removed, and the apparatus turned until the needle is at zero under the influence of the earth's magnetism, i.e. until it lies in the meridian. The magnet must then be replaced and adjusted by its screw until the pointer is again at zero. The magnet-holder should be slid along the scale and stopped at some exact division which will make the deflection somewhere between 15° and 40°.

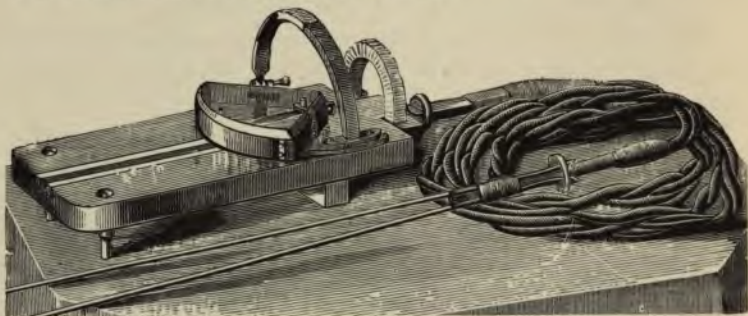


Fig. 16.

To find the number of ampères corresponding to a deflection—

Rule.—*Multiply the number of divisions in the deflection by the number on the magnet, plus* * ·17 *for the horizontal intensity of the earth's field, and divide by the number at the division on the platform scale exactly under the front of the magnetometer.*

In other words, if we call the scale number (i.e. the

* The earth's horizontal magnetic force varies in different localities. The following table gives the number which must be added to the number in the curved magnet when great accuracy is required. For ordinary work the number ·17 may be used.

Cambridge	·181	Newcastle	·167
London	·181	Dublin	·167
Birmingham	·176	Carlisle	·166
Nottingham	·175	Edinburgh	·162
Stafford	·175	Glasgow	·161
Sheffield	·173	Dundee	·161
Manchester	·172	Aberdeen	·158
Liverpool	·171	Inverness	·156
York	·171		

number on the base at the front of the magnet and scale) S, the strength of the magnet M, and the deflection δ, then the current C will be given by the formula,—

$$C = \frac{\delta (M + \cdot 17}{S} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (40)$$

Example.

If the strength of the magnet is 12·24, and the magnet and scale are placed at the mark 3·1 on the base of the instrument, what current is indicated by a deflection of 11° ?

We have from (40),—

$$C = \frac{11 \times (12 \cdot 24 + \cdot 17)}{3 \cdot 1} = 44 \cdot 05 \text{ ampères.}$$

Terminal pieces of the form shown in fig. 16 are attached to the coil of the instrument, and to the electrodes supplied with it. When the electrodes are being removed from the coil or from the leads, the two sides of the spring terminal piece should come into contact with each other before they are out of contact with the plates of the other terminal pieces. By attending to this the circuit is not interrupted, and hence sparks are avoided. A separate terminal piece, shown in the figure with two short wires attached, is also supplied, for the purpose of allowing the galvanometer to be easily introduced or removed from the circuit. This terminal piece is made to form part of the circuit the current through which is to be measured. By adopting this arrangement the galvanometer can be readily removed from one circuit to another.

ELECTRO-MOTIVE FORCE.

If the wires of a galvanometer whose deflection is proportional to the current passing through it, be attached to any two points in a circuit—as for instance, to the wires on the two sides of a lamp, as in fig.

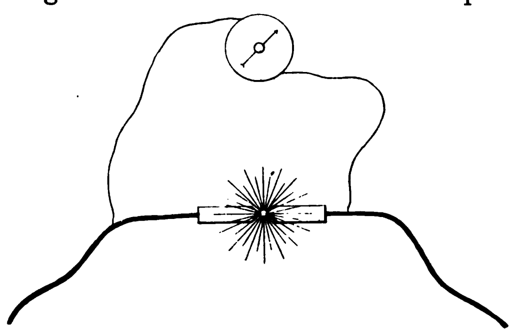


Fig. 17.

17—its deflection will be proportional to the electro-motive force between those two points after the attachment of the galvanometer. If the resistance of the galvanometer is very great compared to that of the lamp, its attachment will not perceptibly disturb the electro-motive force, and therefore the deflection will be a measure of the electro-motive force which is driving the current through the lamp.

For let R be the resistance of the galvanometer, E the electro-motive force between the two points where its wires are attached, and C the current through the galvanometer, then we have from Ohm's law (2), page 12,—

$$E = C\,R$$

In order to make this experiment, it is of course necessary to know what current in ampères is indicated by a given deflection of the needle.

The Voltmeter (Ayrton and Perry's Pattern).

One of the various *Voltmeters* used for measuring electro-motive forces on this principle is that devised by Professors Ayrton and Perry. In appearance it is precisely similar to the ammeter (fig. 15), but its coil consists of a number of turns of very fine wire.

When the roller is placed at "series," the current goes 10 times as often round the needle, and the resistance is 100 times as great as when the roller is at "quantity."

The calibration is performed in precisely the same way as the calibration of the ammeter, except that in the present case the roller is placed at "quantity" for the calibration and at "series" for the actual work, as we wish in work to have as high a resistance as possible, and in calibration to send a sufficient current through the instrument with a moderate number of cells.

Sir Wm. Thomson's Voltmeter or Potential Galvanometer.

This instrument is adjusted and used in the same way as the ammeter or current-galvanometer described on page 47.

It is shown in fig. 18, and consists essentially of a coil

of insulated copper or German silver wire C, the resistance of which is generally over 5000 ohms, fixed to one end of a platform P, on which a magnetometer M rests.

In order to facilitate the use of the instrument, a pair of flexible electrodes, about 4 yards long, are supplied along with it. These electrodes are shown attached to the instrument in the fig. (18). The spring clips attached to the ends of the electrodes allow the instrument to be readily put in

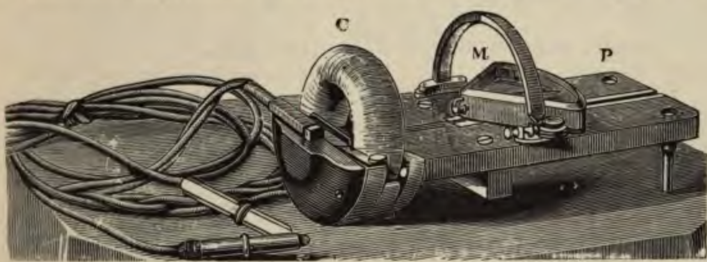


Fig. 18.

contact with two points of a circuit. To prevent a current passing through the coil when no reading is being taken, a spring key is placed in the circuit of the coil. This key should on no account be held long in contact, because the coil becomes heated when a current is allowed to flow continuously through it, and consequently increases in resistance, thus causing the indications to be too small.

To determine the difference of potential between two points of a circuit, an electrode is clipped on at each of the points and then the key depressed and the deflection noted. If the deflection be too great, the magnetometer must be pushed to a division further from the coil; if too small, to a division nearer the coil. *The number of divisions in the deflection is then to be multiplied by the number on the magnets, plus, say* ·17* *for the earth's force, and divided by the number at the division of the scale on the platform exactly under the front of the magnetometer; the result is the difference of the potential in volts.*

In other words, if we call S the scale number, M the strength of the magnet, and δ the deflection (as in (40)), the

* See footnote, page 48.

E.M.F., E in volts, corresponding to any deflection will be given by the formula,—

$$E = \frac{\delta\,(M + \cdot 17)}{S} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (41)$$

Example.

The magnetometer is at the division marked 1·8, the strength of the curved magnet (marked on it) is 11·37, the deflection is 18°; what is the E.M.F.?

We have from (41),—

$$E = \frac{18\,(11{\cdot}37 + \cdot 17)}{1{\cdot}8} = 115{\cdot}4 \text{ volts.}$$

When the difference of potential to be measured exceeds 200 volts, the readings of deflection must be taken as quickly as possible on account of the rapid heating of the coil.*

THE CARDEW VOLTMETER.

Just as these sheets are going to press I have had an opportunity of examining an admirable voltmeter invented by Mr. Cardew, which is equally useful for direct and for alternating currents, and which appears to be very accurate, and which certainly is very sensitive.

It consists of a long, fine platinum-silver wire of high resistance (about 7 or 8 feet long, and ·003 inch in diameter), one end of which is rigidly fixed, and the other is kept tight by a spring, and attached to the axle of an indicating hand. The ends of the wire are connected to the poles. The current heats and expands the wire, and the amount of expansion is shown on the dial. The instrument is so sensitive, that if a dynamo is being driven by a small engine, every stroke of the engine is indicated by a quiver of the pointer.

RESISTANCE.

When feeble currents can be used, and when the resistance under examination is constant, i.e. does not alter with the current, the best method of measuring it is that known as "Wheatstone's bridge." †

* Tables of corrections to apply for the heating are supplied with the instruments, but are not much used.

† Let r be the resistance of each of the 10 coils. When they are in series the resistance is (from 19) $10\,r$; when they are in quantity the resistance is (from 18) $\frac{1}{10}\,r$.

The theory of it is given in my "Electricity."*

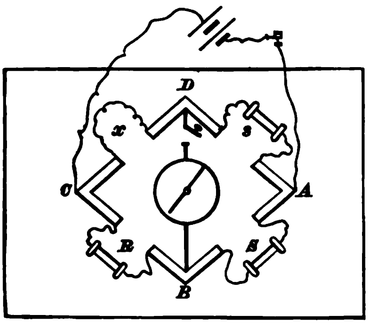


Fig. 19.

The following are practical rules for its use.

Fig. 19 is a diagram of the connections.

Three known resistances and the resistance x to be measured, are connected so as to form the four sides of a square. Two diagonally opposite corners of the square are connected to the poles of a battery, the other two to those of a sensitive galvanometer. It is indifferent to which pair each is connected.

The resistance R is then varied, and we shall find that at one particular value of R there is no deflection of the galvanometer.

When this is the case, *the products of the resistances of opposite sides of the square are equal,* or

$$Sx = sR \quad . \quad . \quad . \quad . \quad . \quad . \quad (42)$$

whence

$$x = \frac{s}{S}R \quad . \quad . \quad . \quad . \quad . \quad . \quad (43)$$

The relative values which we must give to s and S are determined by the range through which we can vary R, and by the relative magnitudes of R and x.

In an ordinary "resistance-box" R can be varied from 1 ohm to 10,000 ohms, and s and S can each be made either 10, 100, or 1000 ohms.

If we knew that x was under 10 ohms, we should probably put $s = 10$ and $S = 1000$. If then we found there was no deflection when R was 721 ohms, we should know that our resistance was

$$x = \frac{10}{1000} 721 = 7{\cdot}21 \text{ ohms},$$

and we have thus measured x to $\frac{1}{100}$ of an ohm.

* 2nd edition, vol. i. p. 247.

If x was 6000 or 7000 ohms, we should probably put $S = 1000$, $s = 1000$; and then if we found $R=6475$ we should have

$$x = \frac{1000}{1000} 6475 = 6475 \text{ ohms.}$$

Lastly, if x were over half a million ohms, we should put $S=10$, $s=1000$; and suppose R were 8452, we should have

$$x = \frac{1000}{10} 8452 = 845{,}200 \text{ ohms.}$$

We see, therefore, with coils such as we have mentioned we can measure from $\frac{1}{100}$ ohm to 1,000,000 ohms.

In practice the Bridge shape is not used, but the resistances are arranged in a "resistance-box" (fig. 20). On the lid of the box are brass blocks of the shape shown in plan in fig. 21. These can be connected by brass plugs inserted at the points a, b - - -.

Fig. 20.

The resistance-coils in the box are connected to the brass blocks in the manner shown in fig. 22. Thus, when the plugs are inserted the current passing through them meets with no resistance. When any one is removed, the current has to pass through the resistance-coil under it.

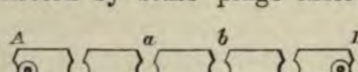


Fig. 21.

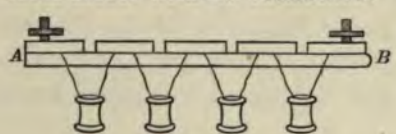


Fig. 22.

The value of the resistance at each opening is marked on the lid of the box, as shown in fig. 23. Thus the resistance *unplugged* is the resistance in circuit. Fig. 23 represents a resistance-box arranged for bridge measure-

ments. The arrangement is precisely similar electrically to

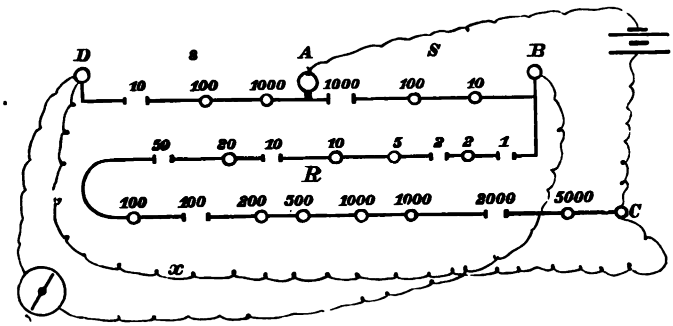


Fig. 23.

that shown in diagram in fig. 19, as may be seen on comparison of the two figs., noting that the same letters are used for the same parts in both.

The arrangement of the resistance R should be noted, by which, with only sixteen coils, any resistance from 1 ohm to 10,000 ohms can be inserted.

In making up any required resistance, the largest number possible should be used first. As fig. 23 is drawn, we have $s=10$, $S=1000$, and $R=2163$, whence when the galvanometer is unaffected

$$x = 21{\cdot}63 \text{ ohms.}$$

Resistance with Strong Currents.

When, as in the case of electric light measurements, the passage of the current considerably alters the resistance, it is necessary to use some method by which the resistance can be measured while a powerful current is flowing through it, and in which it is not necessary to start and stop the current in the course of the observations.

Resistance can be determined by simultaneous observations with the ammeter, or with a tangent galvanometer, and with the voltmeter or other suitable high resistance galvanometer, for the ratio of the two quantities determined is the resistance required. Thus if E be the E.M.F. in volts, between two points in the circuit, and C the whole current in ampères, the resistance between these points is given by the equation,—

$$R=\frac{E}{C} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)^*$$

This method is particularly useful for the measurement of the resistances of electric lamps, which are quite different when they are hot and when they are cold.

Problem.

A certain incandescent lamp requires 42 volts, to send a current of 1·4 ampère through it, what is its resistance with that current ?

We have from (3),—

$$R=\frac{42}{1{\cdot}4}=30 \text{ ohms.}$$

THE OHMMETER.

Professors Ayrton and Perry have arranged an instrument which they call the *Ohmmeter* (fig. 24), in which the needle is

Fig. 24

deflected by a coil carrying the main current, and so corresponding to the coil of the ammeter, but is brought back to zero, not by a constant permanent magnet, but by an electromagnet wound with fine wire, and connected in the same manner as the coil of the voltmeter. The amount of deflection depends on the ratio of the currents in the magnet and

* Page 12

in the coil respectively, that is, on the ratio of the E.M.F. to the current, and so measures the resistance between the two points where the ends of the magnet wire are attached. By properly adjusting the shape of the pole pieces and the position of the coils, the deflections of the instrument are made proportional to the resistance.

Fig. 25 shows the connections.

As at present constructed the magnet wire has about

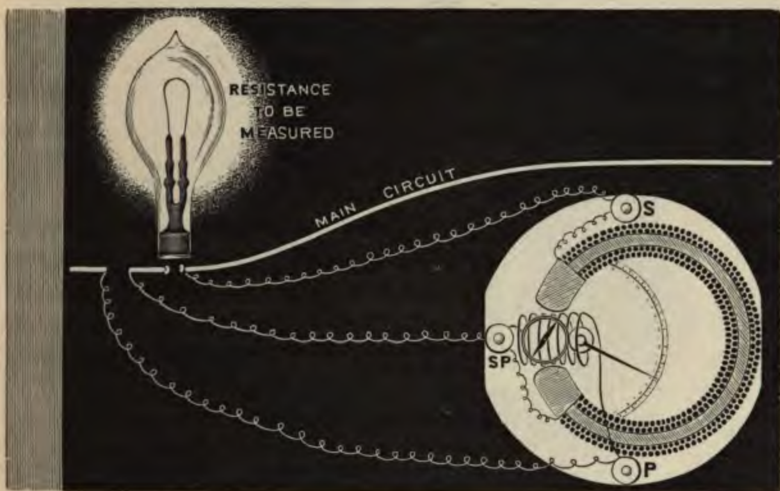


Fig. 25.

700 ohms resistance, and the deflecting coil about ·003 ohm.

It is found that owing to the residual magnetism the needle does not return to zero between different observations, but remains in a position depending on the last resistance observed. This, however, does not affect the accuracy of the observations. The readings are to be taken from the zero marked on the scale, and not from the position of rest.

Thus if the needle indicates 20° in a particular observation, we know that the resistance under examination is that corresponding to 20° deflection, whether the needle before the observation rested at zero or at 10° or at 30°.

Horse-power expended in a Lamp or any other portion of the Circuit.

This can also be determined by the use of the ammeter and voltmeter; for when we know E and C, we know the

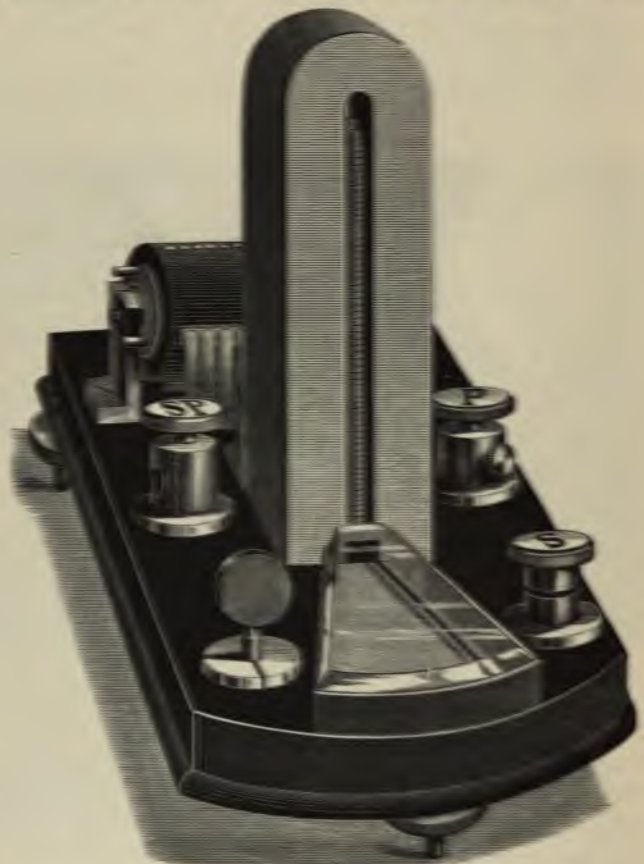


Fig. 28.

horse-power from the equation,—

$$H.P. = \frac{EC}{746} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)^*$$

The Electric-power-meter.

Professors Ayrton and Perry have arranged an instru-

* Page 15.

ment (fig. 26) in which the needle shows the amount of attraction between a fixed coil carrying the main current and a suspended coil of high resistance, which is connected to the two sides of the lamp like the coil of the voltmeter. The attraction between the two coils is proportional to the *product* of the currents in them, or to the product of the main current into the E.M.F., that is to the horse-power.

The fixed coil is wound with 10 turns of wire, which can be connected, either in quantity or series, by means of a roller exactly like that used in the ammeter and voltmeter.

The fine wire coil has 700 ohms resistance, and is placed vertically in the centre of the fixed coil. It turns freely on a jewelled pivot.

In some of the instruments a cog-wheel on the axis gears into another carrying an aluminium pointer so as to multiply the angle of deflection 6 times. The pointer is brought back to zero by means of two spiral springs like those used in chronometers, one on the axis of the turning coil and one on the axis carrying the pointer. By means of a lever one of these springs can be detached so as to increase the sensitiveness of the instrument.

The total range of the pointer is 270°. When the coils are in series and only one spring connected, $\frac{1}{10}$ H.P. moves the needle over the whole scale, or 1° corresponds to $\frac{1}{2700}$ H.P. When the coils are in quantity and both springs connected, a deflection of 270° corresponds to 6 H.P.

We see, therefore, that the instrument will indicate from $\frac{1}{2700}$ H.P. to 6 H.P.

The instrument is graduated in exactly the same manner as the ammeter, by means of the roller and the resistance-coil, whose plug is seen at the left front part of fig. 26.

Thus to sum up,—

The Ammeter measures C.
The Voltmeter measures E.
The Ohmmeter measures the ratio $\frac{E}{C} = R.$*

The Electric-power-meter measures the product EC = 746 HP.*

* I have no experience of the practical working of these two instruments.

We again note, that by means of the first two instruments it is possible to calculate the last two quantities, if the measurements are made simultaneously.

MEASUREMENT OF ALTERNATING CURRENTS.

The strength in ampères of an alternating current can be measured by the Siemens dynamometer (page 35). This instrument is excellent for measuring the powerful currents in arc lamps or in groups of incandescent lamps, but it is not quite so satisfactory when used for the measurement of the currents under 2 ampères used by single incandescent lamps.

The mean E.M.F. of an alternating current can be measured by means of the Cardew voltmeter, or an electro-dynamometer of high resistance might be used, in the same manner as the voltmeter.

For measuring the H.P. expended in any part of the circuit, Ayrton and Perry's Electric-power-meter might be used: owing, however, to self-induction,* neither the power-meter nor the high resistance dynamometer are quite satisfactory.†

In my own experience I have found that a useful way to measure the electric current, electro-motive force, or horse-power used in an incandescent lamp by an alternating current, is to note the candle-power exactly, and then to bring the same lamp to the same brightness by a Grove battery or by a direct-current machine, and to make the necessary measurements on the direct current by the methods already described.

The battery is preferable to the machine for some reasons, but the machine has the advantage of being always ready in the factory, and can be started by merely pulling a lever, whereas 30 or 40 Groves cells take perhaps an hour to set up. With the battery the current is regulated by altering the number of cells; with a machine it is adjusted by introducing different resistances, or by varying the speed, if the machine is driven by an independent engine.

* See Chapter IX.

† The Cardew voltmeter is practically not affected by self-induction.

CHAPTER VI.

INCANDESCENT LAMPS.

The class of lamps known as "incandescent" consists of a thin filament or wire of carbon enclosed in a glass globe from which the air has been exhausted.

On a suitable current of electricity being sent through the filament it becomes white hot, or incandescent, and gives a light of from 1 to 100 candles according to its surface, and for a given surface according to the temperature to which it is raised. For a given temperature the durability of the filament depends on its uniformity, and on the completeness with which the air has been exhausted. Below a certain temperature, nearly corresponding to that of melting platinum, a well-made filament in a good vacuum is very durable. Under these conditions, lamps last six or twelve months of ordinary domestic work.

The chief incandescent lamps now in actual use are the Swan, Edison, Maxim, Lane-Fox, Woodhouse and Rawson, and Crookes. They differ from each other in the methods of preparing the carbon filaments and in other details.

Each inventor has patented his processes of manufacture, but I shall purposely abstain from expressing any opinion as to the validity of some of the patents.

I propose to give a general description of one or two of the lamps which may be considered as typical ones, and to describe some of the processes used in their manufacture.

I shall, however, avoid technical details as much as possible, partly because I have not practical experience of the processes, and partly because it is not so much important for electrical engineers to be prepared to manufacture

lamps, as to be able to erect and manage them when they are supplied by the present manufacturers.

The first public exhibition of incandescent lamps that was made in this country was made by Mr. Swan before the Society of Telegraph Engineers on November 24, 1880. The first exhibition in America was made by Mr. Edison.

Incandescent Lamps.—The Carbon.

In all incandescent lamps the filament consists of a thread of some vegetable substance which has been *carbonized* by heat.

The Terminals.

The ends of the filaments are connected to two platinum wires, which pass through the glass and are melted on to it. Platinum is used as, its expansion rate being about the same as that of glass, the latter does not crack in cooling.

The Exhaustion.

The life of the lamp depends in a large measure on the goodness of the vacuum. In order to get a good vacuum, various modifications of the Sprengel mercury-pump have been made, all having for their object to fit an instrument hitherto only used in laboratories to the more rapid processes of the factory.

Hot Exhaustion.

It was soon found that however perfectly the lamp was exhausted when cold, yet that the first time a current was sent through it a quantity of gas was driven out of the carbon itself, which injured the vacuum and caused the speedy destruction of the filament.

To surmount this difficulty the following plan was adopted, first, I believe, by Swan, and is now used by all makers of incandescent lamps. While the lamp is still attached to the pump a current of electricity is sent through the filament, sufficient to raise it to a somewhat higher degree of incandescence than will be used in actual work. All the gas driven out of the carbon is at once removed by the pump, and the lamp is sealed while the current is still passing.

PLATE IV.—THE SWAN LAMP—OLD PATTERN.

The Swan Lamp. (Plates IV. and VI.)

The first incandescent lamps exhibited in England were, as we said before, those shown by Mr. Swan to the Society of Telegraph Engineers on November 24, 1880. The form of lamp then exhibited is shown in Plate IV. It has been greatly improved upon since, but the old form is of so great an historical interest that I have given a somewhat full description of it.

Plate IV. shows an old Swan lamp of 25-candle power, full size. Fig. 27 shows some of the details of it on an enlarged scale.

The Filament.


Fig. 27.

The filament consists* of a flat plait or round thread of cotton, which is parchmentised by immersing it in a mixture of two parts of sulphuric acid to one of water. The thread is left in the acid just long enough to effect the required change, and then removed, and quickly and thoroughly washed in water, so as to remove the last trace of acid.

This operation has the effect of completely destroying the fibrous character of the cotton, so much so that the parchmentised thread after drying becomes smooth and transparent like silkworm gut. Before it is carbonized, the parchmentised thread is passed through dies, which reduce it to a uniform cross section. It is then wound on rods of carbon or earthenware, so as to give the required form to the filament preparatory to carbonization. The most usual form so imparted to the filament in this manner is the loop and spiral represented in Plate V.

The ends of the filament are thickened, by having either more thread or some bibulous

* Swan's Specification, No. 4933, Nov. 27, 1880.—All specifications are published by the Commissioners of Patents, Sale Department, 38, Cursitor Street, Chancery Lane, E.C.

paper wound round them, either before or after the thread is carbonized. The thickened part is carbonized in the same manner as the filament itself.

Carbonization of the delicate filaments wound round the rods as described is effected by burying them in a mass of powdered charcoal contained in a crucible, and then raising to a very high temperature in a furnace during several hours.

In mounting the filaments, the thickened ends are inserted into split metal tubes, which are made to clip them tightly by means of a sliding ring. The two tubes are continued as half-tubes, as seen in fig. 27 and in Plate II., and form the conductors by which the current is conveyed to the carbon. They are supported by being tied to a glass rod which forms part of the neck of the lamp. Platinum wires are attached to the upper ends of the metal tubes, and pass out through the glass, being melted into it. In order to prevent any leakage, little platinum caps were fixed to the wire just where it comes through the glass, and melted on to the glass outside.

The reason of having so long a neck to the lamp, was that it was thought if it were shorter sufficient heat might be conducted from the carbon to the platinum wire and cap to risk cracking the glass.

The Exhaustion.

In order to exhaust the air, a tube, with a narrow neck or contraction in it, is left attached to the globe. This is connected to a Sprengel or other suitable air-pump. After the lamps have been under exhaustion for about half an hour, the vacuum is tested by an induction coil, and if found to be non-conducting, the blow-pipe is again applied at the point of junction of the lamp with the exhaust tubes, and the two are gently drawn asunder. This is so managed that a very short spike is left at the point of severance. This spike forms the little point seen at the bottom of Plate IV.

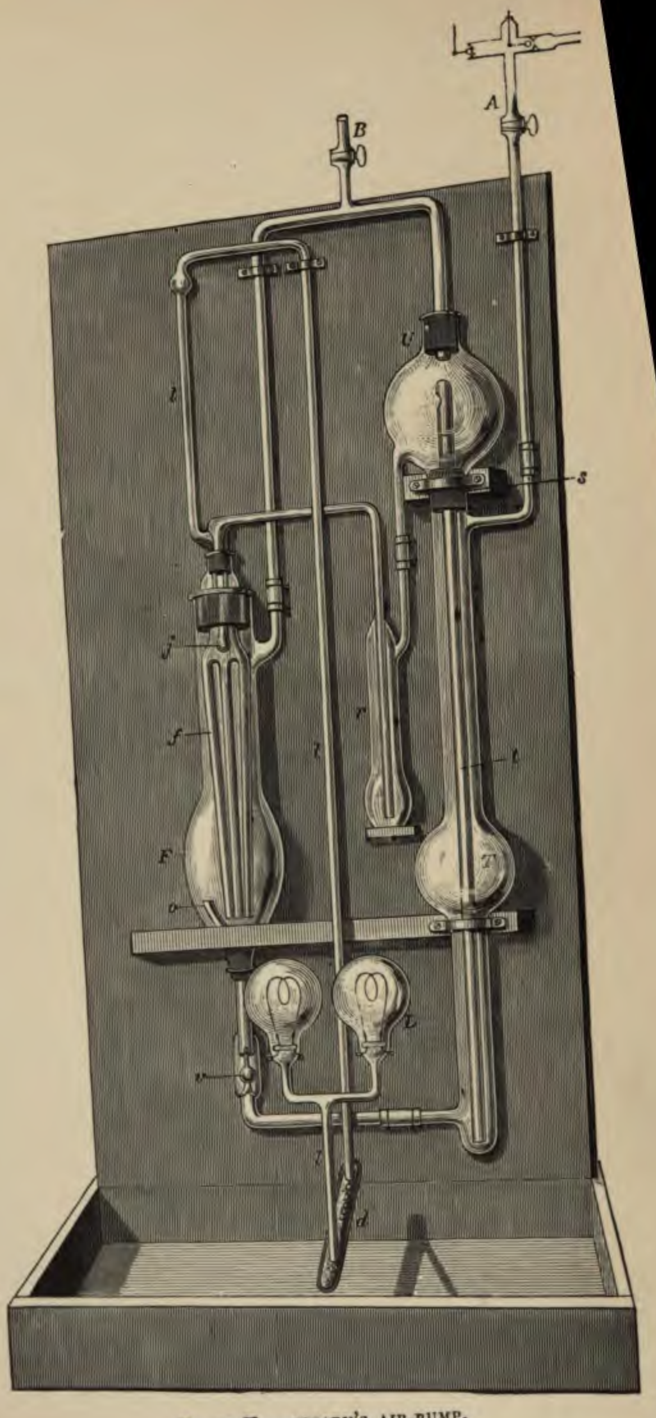


PLATE V.— STEARN'S AIR-PUMP.

The Air-Pump (Stearn's Improved Sprengel).
(Plate V.)

The ordinary Sprengel pump consists of glass tubes down which mercury flows in a broken stream or in drops. Near the top of the tubes are side openings connected to the chamber to be exhausted. Air enters from this chamber, and becoming compressed between consecutive mercury drops, is carried away, and the process is repeated until the chamber is completely exhausted.

In the ordinary form of the Sprengel pump the action is very slow, particularly in the later stages, and as the mercury at the bottom end of the tube is exposed to the atmospheric pressure, the tubes have to be over thirty inches high, in order that the weight of the column may overcome that pressure.

In Mr. Stearn's improved form of the pump (Plate V.), used in the manufacture of Swan lamps, the mercury is automatically raised to the overflow level by atmospheric pressure, the atmospheric pressure upon the outgoing mercury being decreased by connecting the outflow tube to a vacuum produced by an ordinary mechanical air-pump.

Plate V. shows Mr. Stearn's pump in detail; its action is as follows:—

Mercury is put into the outer tube on the right till it nearly fills the bulb T. It is prevented from rising on the left hand tube by the valve *v*. The inner tube *t* passes through an air-tight stopper at *s*.

The tap B is first opened so as to remove the greater portion of the air from the bulbs T, U, *r*, and F.

B is then closed and A opened. This causes the mercury to spout up through the tube *t* into the bulb U, whence it flows through the vessel *r* and out of the jets *j*, and through the fall tubes *f*, carrying with it the residue of the air *and also the air from the lamp-tube l and from the lamps LL.* The air thus sent into the reservoir F is drawn thence through B to the vacuum chamber by the mechanical pump. By the action of an automatically worked two-way cock, A is periodically and alternately

connected to the atmosphere and to a vacuum chamber in which the vacuum is maintained by the action of a mechanical pump.

This causes the valve *v* to alternately open and close, and, consequently on this periodical action, the mercury flows through the overflow tube, and in this way a continual supply of mercury is given to the fall tubes.

d is a drying tube to remove moisture. The trough at the bottom of the pump is to catch the mercury in case of a tube breaking.

Mounting.

For convenience in attaching the lamp to the wires bringing the current to it, the stem of the old lamp (Plate IV.) was enclosed in a cardboard tube about ⅛ inch thick. Brass springs attached to the two sides of this were connected respectively to the two platinum caps, by means of the little screws seen at the top of Plate IV.

At the end of the wall-bracket or other stand which carried the lamp was fixed a wooden tube, into which the paper tube on the lamp just fitted. Inside this wooden tube were two metal plates, to which were attached the wires supplying the current.

When the lamp was put into position, by having its stem slid into the tube, the springs pressed on the metal plates, and at once made the connection.

We see that in case of a lamp breaking down, it could be removed and a new one substituted by any servant, and without the necessity of employing a person who understands electrical connections. The lamp can of course be used either side up, or horizontally, or in any other position that is preferred.

Efficiency.

The 20-candle lamps of the old pattern had each a resistance of from 45 to 150 ohms when cold; or 25 to 75 ohms when hot. They required from 1 to 1½ ampères of current, and 30 to 50 volts E.M.F.

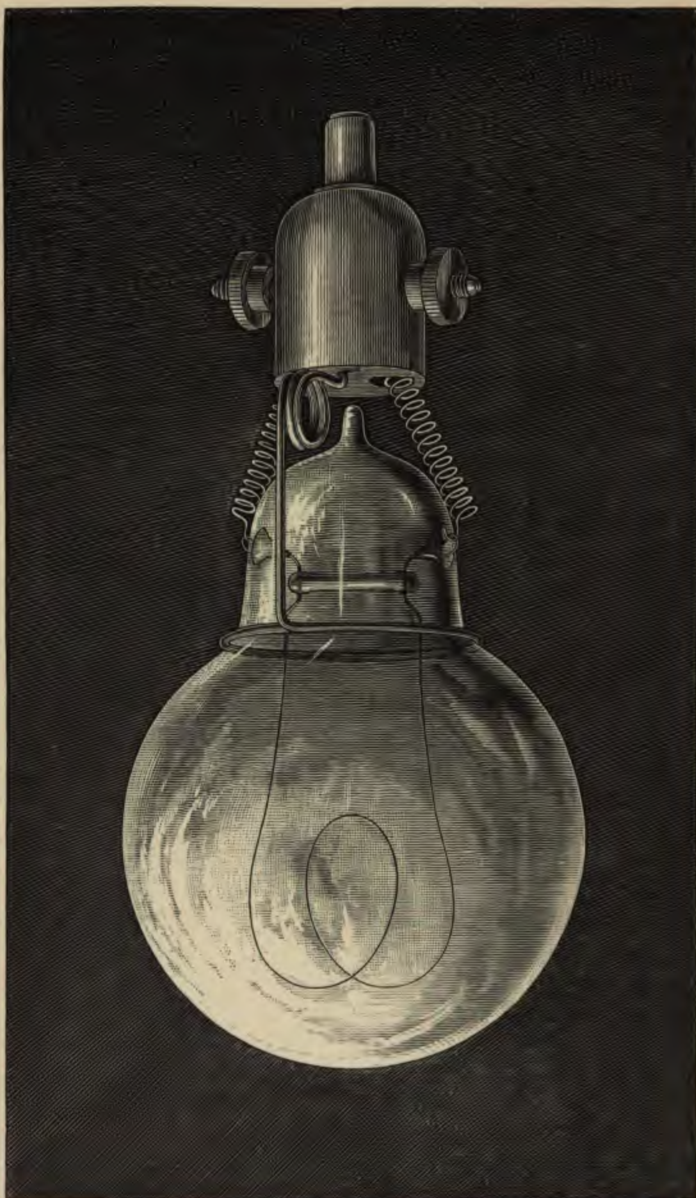


PLATE VI.—THE SWAN LAMP—NEW PATTERN.

To determine the horse-power absorbed in a lamp we make use of equation (7), page 15,—

$$\text{H.P.} = \frac{E\,C}{746}.$$

For example: What horse-power is expended in a lamp requiring 45 volts and 1·5 ampère?

We have from (7),—

$$\text{H.P.} = \frac{45 \quad 1{\cdot}5}{746} = {\cdot}091,$$

or a little less than $\frac{1}{10}$ H.P.

CURRENT, E.M.F., AND COPPER.

The horse-power expended in a lamp depends on the product of the current into the electromotive force at which it is supplied, and is therefore the same as long as the product is constant, whether the E.M.F. is small and the current large, as in the old pattern, or *vice versâ.* We note that the higher the resistance of the filament, i.e. the longer and thinner it is, the more E.M.F. is required to drive the current through it, and the less current is required to produce a given quantity of energy in the form of heat and light in the lamp.

The quantity of copper required for a conductor of given length depends only on the current it has to carry, and not on its E.M.F. *We thus see that every improvement in the lamps which enables the filament to be made thinner and longer, and so diminishes the current used, proportionably diminishes the quantity of copper in the mains.* As this copper is one of the most expensive items in an electric light plant, improvement in this direction is extremely important.

THE NEW SWAN LAMP, 1883 PATTERN. (Plate VI.)

Since the introduction of the original Swan lamp, several modifications have been made in its form and other details. Plate VI. represents the latest form, in which the filament is much longer and thinner than in the old pattern, being about five inches long and ·005 inch in diameter. It

requires an E.M.F. of 100 to 120 volts to bring it to normal incandescence of 20 candle-power.

Process of Manufacture.

Figs. 28 to 33 show the manner in which the several parts of the new Swan lamp are put together.

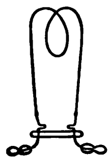


Fig. 28.

The filament is attached to its platinum wires and mounted on a glass bridge, as in fig. 28, little beads of glass being also formed on the wires where they are to pass through the walls of the lamp.

The globe is blown as in fig. 29, and with a sharp file is cut into two pieces, as in fig. 30.

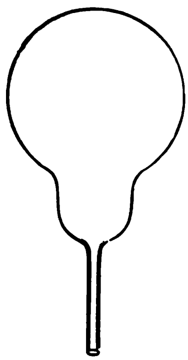


Fig. 29.

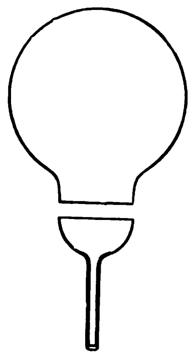


Fig. 30.

The carbon and platinum wires are inserted, and the latter fused on by the blow-pipe, as in fig. 31.

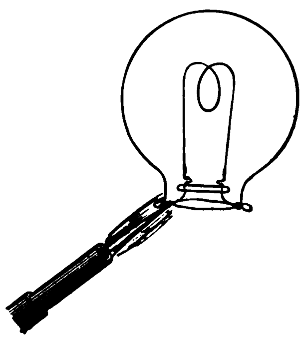


Fig. 31.

The two portions of the globe are joined again by the blow-pipe, as in fig. 32, and the lamp is completed

Fig. 32.

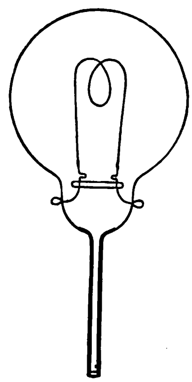


Fig. 33.

in the form shown in fig. 33, and is ready to attach to the pump.

The following are the results of some experiments in the efficiency of the new Swan lamp :—

Candle-Power of Lamp.	Current in Ampères.	E.M.F. in Volts.	Resist. in Ohms. (Hot.)	Volt-ampères per Candle.	Candles per H.P.	Lamps per H.P.
16	·62	98	158	3·74	199	12
16	·63	97·1	154	3·69	202	12
16	·726	78	107	3·5	213	12
18	·63	100	158·7	3·5	213	12
18	·64	99·1	154·8	3·52	212	12
18	·75	80	107	3·3	226	12
20	·65	102	157	3·32	225	11
20	·66	100	151·5	3·3	226	11
20	·76	82	108	3·1	240	12

It will be noticed that in the new types of Swan lamp the connection between the platinum wires and the carbon filament is altered from the original type. The carbon filament is in the new types connected directly with the platinum wires which pass through the stem of the glass bulb.

The Holder.

A great number of holders of different forms are in use. The one which I have adopted, after experience of a great many, is shown in Plate VI., about full size. It consists of a block of box-wood, to which is fixed a spring wire with a ring which goes round the neck of the lamp, and two springs, one of which hooks into each of the platinum rings of the lamp. These contact springs are attached to little brass binding screws at the sides of the wood.

It is important that both the contact wires should be springs, as if, as was the case in some of the earlier holders, they are made simple hooks, then the pressure of the spring which holds the neck of the lamp secures a good contact with one terminal only, and any vibration breaks contact at the other.

SPECIAL LAMPS.

Figs. 34 and 35 represent miniature lamps mounted for surgical purposes. In these lamps water circulates in the space between the lamp itself and an outer glass tube, to keep the lamp cool enough to permit of its introduction into the internal parts of the living body. Miniature lamps have been set in brooches and shirt studs and also made to form the petal of an artificial flower.

Fig. 34.

Lamps somewhat larger than these, of about $2\frac{1}{2}$ candle-power, in connection with small portable accumulators of two or three cells, have been used for stage effects.

Fig. 35.

Swan lamps have been made with the carbon filament so short that two volts have sufficed for rendering them incandescent, and which can therefore be used with one or two cells of a battery. Mr. Stearn, the coadjutor of Mr. Swan, has applied such lamps to the microscope.

Fig. 36 represents a microscope lamp mounted on a stand.

Fig. 36.

SWAN'S MINER'S LAMP.

Figs. 37 and 38 illustrate a lamp arranged by Mr. Swan for use in fiery mines. The ordinary lamp is enclosed in a massive globe of very thick glass, surrounded by wire guards. In case of the lamp itself being broken, the air

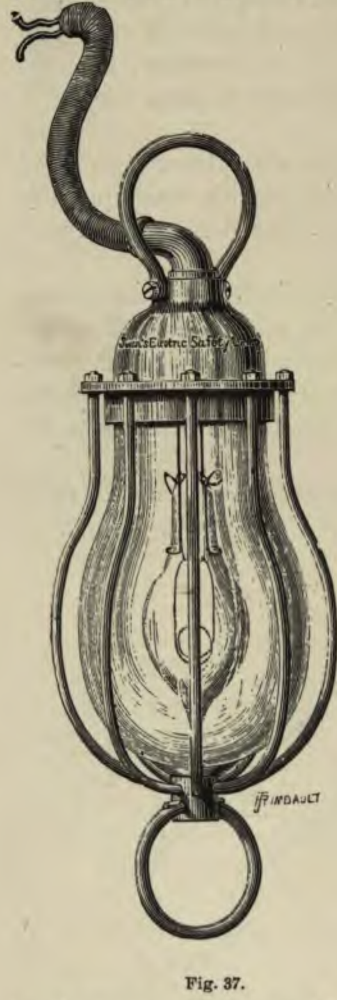


Fig. 37.

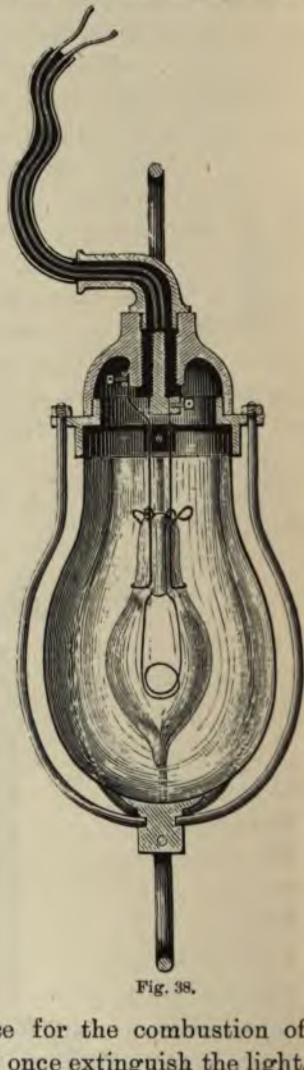


Fig. 38.

in the outer globe would suffice for the combustion of the carbon filament, and would at once extinguish the light. The only danger attending the use of this lamp is, that if the wire bringing the current to it were to be accidentally

broken, a spark would occur between the broken ends and might fire the mine; or a spark might be produced if the naked wires were exposed, and metallic connection accidentally made and broken between them—as, for instance, by a man dropping a pick or drill upon them, and picking it up again. To guard against these dangers the wires are made very strong, and are very thickly covered with insulating material.

The lamp is also used by divers in submarine work.

The Edison Lamp.

The Edison lamp is shown in fig. 39. The carbon filament is generally prepared from a strip of bamboo, which is cut to the right shape, and has thickened ends left on it. Sometimes it is made from paper or cardboard.

Whatever substance is used is carbonized by being placed in a crucible surrounded by powdered charcoal, and raised to a high temperature in a furnace.

There is an essential difference between the Swan filament and the Edison. In the Edison filament the cellular structure of the fibrous material is preserved. In the Swan it is effaced by the process of parchmentization.

The thickened ends being cemented on to the platinum-wire, the joints are electro-plated with copper to ensure good contact.

Fig. 39.

The lamp is exhausted in much the same manner as the Swan lamp.

The method of connecting the lamp to the line wires is as follows. The screw, and the conical collar seen just above it in fig. 39, are insulated from each other, and are connected respectively to the two ends of the filament. The screw socket in the wall bracket is connected to one of the line wires, and a hollow metal cone just above it is connected to the other. On the lamp being screwed into its socket, one contact is completed through the screw, and the other through the cones, which press one into the other as the lamp is screwed home.

The lamps are at present made in two sizes of 8-candle and 16-candle power respectively.

The following are details of experiments on six of the 16-candle Edison lamps :—

	No. on Lamp.	Candle-Power.	Resistance. Cold.	Resistance. Hot.	Volts at Lamp.	Current. Ampères.	Energy. H.P. Expended.	Candles per H.P., or Efficiency.
Short Filament.	1	8	105·3	58·8	51	·868	·0593	135
	2	8	97·7	57	51	·896	·0612	131
	3	8	95·8	58·4	51·5	·882	·0609	131
Long Filament.	4	16	257·6	144·2	105	·728	·1024	156
	5	16	272·7	150·7	105·5	·700	·0989	162
	6	16	242·5	141·5	105	·742	·1044	154

This gives an average of 145 candles per H.P. expended in the lamp.

Efficiency and Durability.

In comparing the amount of light per horse-power given by different incandescent lamps, we must remember that we can increase it up to almost any amount we please by working the lamp at a higher temperature, only by so doing we reduce the life of the lamp from six months to perhaps three months, or a few weeks, days, hours, or minutes. Only experience can show us what is the most economical temperature to work at, having regard both to the cost and trouble of renewing the lamps, and to the cost of the electric current which works them. This, "the temperature of maximum economy," will vary with the price of coal, being highest in places where coal is dearest, and *vice versâ*. It will be lowest of all where water power is used instead of steam to drive the dynamos.

Temperature Scale for Incandescent Lamps.

The efficiency of a lamp depends on the temperature to which it can be worked. We have, however, no means of measuring these high temperatures on the ordinary scales; nor, if we had, would it be of much use to us.

I have therefore suggested * that the temperature of the filament of an incandescent lamp could be measured by the ratio of the horse-power expended on it, to its surface; † and

* *Electrician*, Jan. 14, 1882. † See Eq. (30), page 79.

that companies, if they were to give guarantees of durability, might write them in the form :—"These lamps will last for six months, at a temperature not exceeding such-and-such a horse-power per square inch of surface."

A lamp with an efficiency of 150 candles per H.P. would use about 1 H.P. per square inch of surface.

Example.

A 15-candle Lane-Fox lamp has a surface of $\frac{1}{10}$ square inch, a resistance of 45 ohms hot, and takes a current of 1·3 ampère. From equation (4) we have,—

$$\text{H.P.} = \frac{1{\cdot}3 \times 1{\cdot}3 \times 45}{746} = \frac{1}{10} \text{ almost exactly.}$$

Thus 10 lamps give 150 candles, have 1 square inch surface, and take 1 H.P. to work them.

Fig. 40.

THE MAXIM LAMP.

Fig. 40 shows the Maxim lamp mounted on a wall-bracket.

Figs. 41, 42 show the method of attaching the carbon to its supports. The ends of the carbon are flattened, and are held by nuts. As it is difficult to obtain a good contact between platinum and the hard carbon of which the lamp filaments are made, Mr. Maxim introduces washers of soft carbon between the filament and the nut and bolt.


Fig. 41.

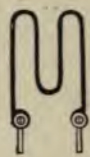


Fig. 42.

In the Maxim system the filament is carbonized by heating in the usual way, but during the whole process it is kept surrounded by an atmosphere of gasoline or other gas rich in carbon; and when the lamp is completed and has been exhausted, gasoline vapour is let in and pumped out again. When this has been repeated two or three times every trace of oxygen is removed from the globe, and the residual gas in the vacuum is pure gasoline.

Fig. 43 shows the arrangement used for carbonizing.

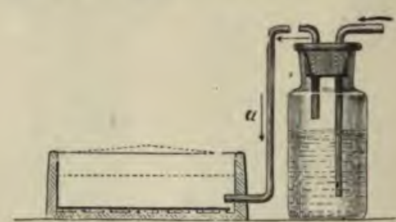


Fig. 43.

There is a flat crucible, in which the cardboard strips, previously cut to the right shape, are placed. They are laid between sheets of cardboard, and these again between metal plates. The metal plates are somewhat smaller than the crucible, so as to allow the carbon gas to circulate round them. The layers of metal and cardboard about two-thirds fill the crucible, which is then filled up with sand.

The gas is supplied by causing ordinary coal gas to

bubble through a bottle, containing gasoline or other volatile hydrocarbon oil.

"The carbonizer thus filled is placed over a gas flame or upon a stove, and heated to a temperature sufficiently high to expel the aqueous vapour contained in the pores of the material, but not sufficiently high to char the material to any considerable extent, and the carburetted gas is admitted to the carbonizer through the pipe *a*, fig. 43, and ignited, where it escapes through the sand at the top. After the material has been subjected to this heating for a considerable time, say ten or twelve hours, the carbonizer is placed in a muffle-furnace and raised to a white heat, and kept there until all the material is thoroughly charred, the gas being all the time supplied to the carbonizer through the pipe, and circulating about the forms so as to envelope them on all sides.

"The function of the gas during the first part of the process is to all appearance to permeate the pores of the material and drive out the aqueous vapour and air contained in them as far as possible: and its function during the latter or charring part of the process seems to be to protect and consolidate the carbon of the material. When the hydrogen and other constituents are dissociated from the carbon of the material by the heat of the furnace, the surrounding hydrocarbon vapour or gas is also apparently decomposed; and some part of the carbon thus liberated, especially that which is contained in the pores of the material, is apparently deposited upon the carbon of the forms, and serves to consolidate it. The hydrogen when liberated does not corrode the carbon of the forms; but if it has any tendency to again take up carbon, probably unites with some part of the free carbon liberated from the gas or vapour."*

When the lamp is completed, the first effect of the passage of the current is to decompose the trace of vapour left in the globe, and deposit the carbon from it on the heated filament. The inventor considers that "an almost absolute vacuum is thus established in the globe."

As the hottest points in the filament are the points where it is thinnest, and therefore weakest, more carbon will be

* Maxim's Specification, No. 1649, April 21st, 1880.

deposited on these points, and therefore the action tends to correct any unevenness in the carbon.

It has been frequently stated that Maxim's lamp can be run at a higher temperature—that is, can give more light per horse-power—than either Edison's or Swan's. This may possibly be the case, but I am not aware of any experiments confirming this view. It is true that Professor Ayrton * has published an account of experiments where these lamps were run at enormous temperatures, and had a correspondingly high efficiency. The experiments, however, only lasted a few minutes, and the temperatures were generally increased until the lamp broke. The figures obtained from them therefore give no information as to what would be the efficiency of the lamp at its normal temperature—or, in other words, at what temperature a company would work the lamp, if they were giving a guarantee that it should last six months.

The Lane-Fox Lamp.

Mr. Lane-Fox's process is probably not very different from that adopted by other manufacturers. As it happens, however, that I have had an opportunity of inspecting it somewhat closely, I will describe it in detail, not saying that it is better or worse than other processes, but as an illustration of what the general nature of all the processes is.

The filaments are usually prepared from the fibres of the bass broom.

About 100 pieces of fibre, cut to the right length, are bent round a block of carbon, and secured to it by winding string round, as shown in fig. 44. Some fifty of these blocks are prepared, and placed in layers one above another in a crucible, all the interstices between them being filled with powdered charcoal, with which also the crucible is filled up to the top.

Fig. 44.

* *Engineer*, November 25, 1881.

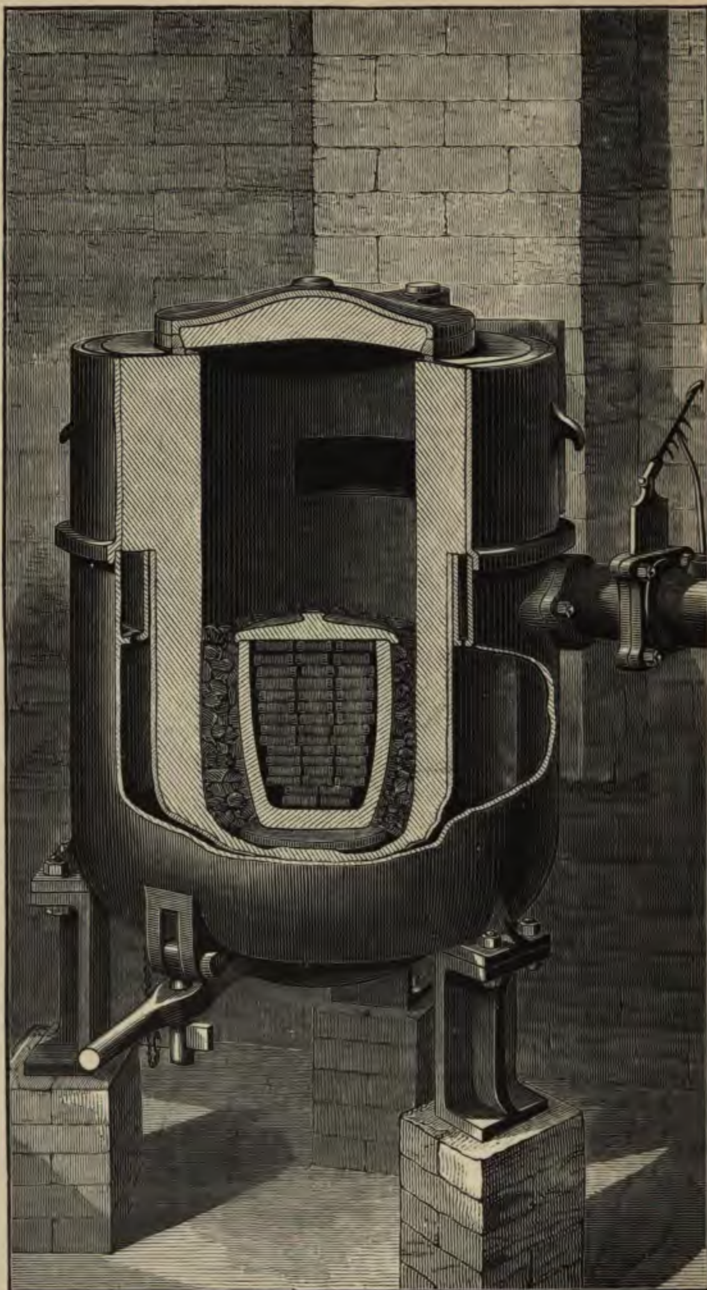


PLATE VII.—FURNACE USED IN MANUFACTURE OF LANE-FOX LAMPS.

The crucible is then placed in a small furnace (Plate VII.), and the temperature gradually raised up to full whiteness. The crucible, with its contents, is kept at a full white heat for some twenty minutes, after which it is allowed to cool. On being taken out, the fibres are found to be converted into hard carbon of a rough, porous texture and of high and unequal resistances.

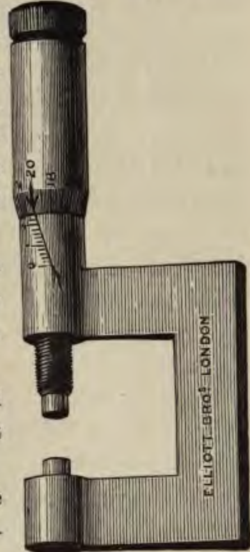


Fig. 45.

Plate VII. shows the details of the arrangements of the furnace used by Mr. Lane-Fox as constructed by Messrs. Fletcher.

We note that there is a perforated diaphragm which causes the draught to circulate evenly round the crucible.

A furnace and crucible of the size shown will carbonize about 5000 filaments at one heating.

The next process is to gauge the fibres with a wire gauge reading to $\frac{1}{1000}$ inch (fig. 45); they are then sorted, so that all of the same diameter are placed together for the making of lamps of the same radiating surface.

If S be the surface, L the length, and D the diameter, we have,—

$$S = 3{\cdot}1416 \, D \, L \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (44)$$

Example.

A filament is 2 inches long and ·018 inch diameter, what is its surface?

We have from (44),—

$$S = 3{\cdot}1416 \times {\cdot}018 \times 2 = {\cdot}1031 \text{ of a square inch.}$$

The next operation is the equalizing of the resistances, and the hardening and smoothing of the carbon. This is accomplished by means of what is called a flashing-bottle.

The carbons are placed, one by one, with their two ends

in two spring clips, so that a current can be sent through them. These clips are fixed into a cork, so that they can be placed inside a bottle, through which a stream of coal-gas is constantly flowing.

On a current being sent through the filament so as to render it incandescent, carbon from the gas commences to deposit on it, and the filament becomes denser and smoother, and its resistance rapidly diminishes. The process is stopped when the resistance has reached exactly the desired amount. As the resistance diminishes, the brightness of the light given by the filament in the flashing-bottle increases.

When the workman, judging by the light, considers that the resistance has reached its proper value, he removes the filament from the bottle and tests its resistance (cold) by a Wheatstone's bridge. After a little practice the workmen are able to obtain the resistance correct to about one ohm, by judging the brightness of the light, in one or two tries, or "flashes," for each filament.

By means of the ohmmeter,* it might be possible to obtain the hot resistance accurately without taking the filament out of the bottle.

The thickened ends of the filaments consist of two little cylinders of carbon, which are drilled from end to end. The ends of the filament are inserted into the holes at one end of each cylinder, and the platinum wires which pass through the glass of the lamp are inserted into the other ends. The filament and platinum wires are secured by a cement of which Indian ink is the chief ingredient.

The construction of the glass part of the lamp is seen in Plate VIII. and in figs. 46 and 47.

The globe is prepared with a sufficiently wide neck to admit the carbon loop (which is sufficiently elastic to be considerably bent without breaking).

A glass piece (fig. 46) is prepared, having two narrow tubes, into the points of which are melted little pieces of platinum wire, about $\frac{3}{16}$ inch long. The carbon is

* Page 56.

PLATE VIII.—THE LANE-FOX LAMP.

attached to these wires in the manner already described, and the forked piece being inserted in the globe, the neck of the globe is melted on to the wide part of it in a blow-pipe flame. The upper piece is taken off, so that the neck is hollow and funnel-shaped, as shown in fig. 47.

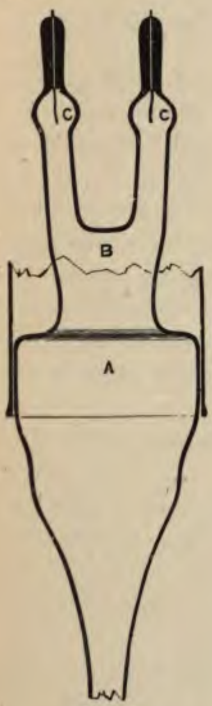


Fig. 46.

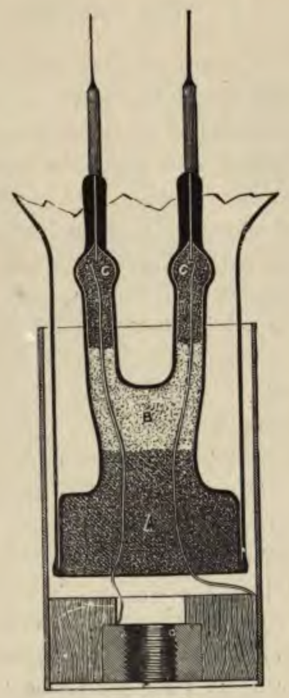


Fig. 47.

A fine tube is then melted into the side of the neck for exhaustion. A little mercury * is put from outside into each of the tubes of the forked piece, and copper wires put in so as to dip into the mercury at C. The mercury forms an electrical connection between the copper and platinum, and at the same time prevents any leakage ot air where the platinum passes through the glass. The hollow neck

* The whole of this part of the process is antiquated, but it is of some historical value as showing the difficulties w hich had to be overcome in the early days of lamp manufacture.

is filled up with cotton-wool (B), and with plaster of Paris (A), which holds the copper wires and the mercury in their places. The lamp is now ready for exhaustion.

This is accomplished by means of a pump invented by Mr. Lane-Fox, and shown in Plate IX.

THE LANE-FOX PUMP. (Plate IX.)

The pump consists essentially of two large globes connected by a tube, partly of glass partly of india-rubber. The glass part (A) of the tube is vertical, and is some 35 inches long, and one globe is fixed at the top of it. The other globe is moveable, and is connected to the lower end of the fixed glass tube, by a length of india-rubber tube sufficient to allow the moveable globe to be hung by its wire handle to either of two hooks, one of which brings it above the fixed globe, while the other is below the level of the bottom of the fixed glass tube. The top of the moveable globe is open to the air.

Enough mercury is put in the apparatus to fill the tube and one globe.

A side tube branches out from the fixed tube near the top, and turns up and passes vertically a little higher than the top of the fixed globe.

A lamp, or generally two lamps at a time, are attached to the top of this tube.

In the vertical part of the side tube is a valve consisting of a cylindrical enlargement, inside which lies a hollow glass stopper. On mercury rising in the side tube, the stopper floats up and closes the tube sufficiently tight to stop mercury from passing up to the lamps. The mercury surrounding the stopper prevents air passing it.

At the top of the fixed globe is a valve worked by hand, consisting of a glass stopper surrounded by a second smaller globe. To close the valve the stopper is inserted, and a little mercury or sulphuric acid put in the smaller globe surrounding it. The stopper prevents the liquid from passing from the small to the large globe, and the liquid prevents the entrance of air.

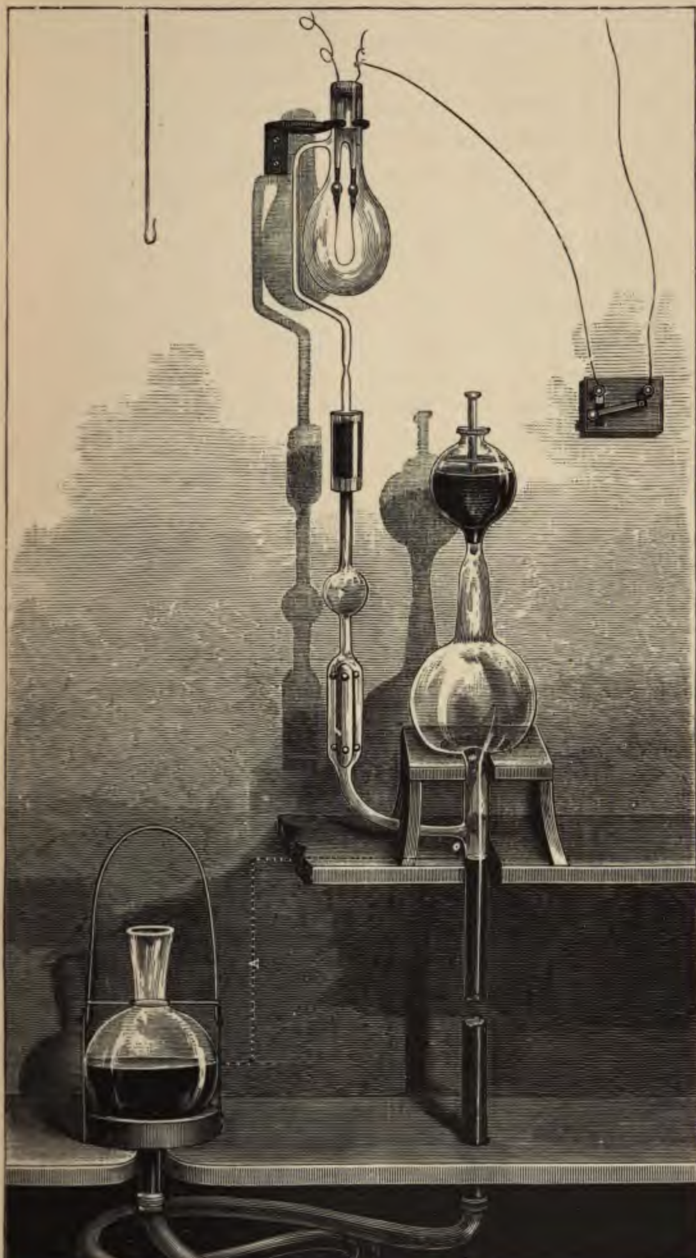


PLATE IX.—LANE-FOX'S AIR-PUMP.

When the pump is worked, the moveable globe is hung on the upper hook, so that the mercury rises in the fixed tubes. In the side tube it rises as far as the valve, which it closes; while in the main tube it rises and fills the fixed globe, the stopper being withdrawn to allow the air to escape.

Some strong, pure sulphuric acid is then put into the smaller globe, and the moveable globe lowered sufficiently to allow a little of the acid to enter the large fixed globe, where it lies on the top of the mercury. The stopper is then inserted, and the moveable globe completely lowered and hung on the lower hook.

The mercury sinks, leaving a complete vacuum in the upper globe until the column is lower than the opening of the side tube, when the valve in the latter opens and the air in the lamps rushes into the large globe.

The moveable globe is then again raised, and the rising mercury closes the valve leading to the lamp; and the air, being directed into the fixed globe, escapes through the stopper valve, which is opened for the purpose. Meanwhile the sulphuric acid removes every trace of moisture. We see that the ratio of the quantity of air in the lamp after each stroke is, to that before the stroke, as the volume of the lamp is to the sum of the volumes of the lamp, tube, and fixed globe.

After a few minutes' work the lamp is completely exhausted, as is shown by the sharp click with which the mercury strikes the top of the fixed globe on the moveable globe being raised.

The filaments are then brought to a state of vivid incandescence, and the pumping recommenced, and continued for a few minutes more, until the greater portion of the gas contained in them has been expelled and removed. They are, however, kept on the pump and incandescent for some twelve hours, a stroke being taken only occasionally to remove the last trace of gas. The lamps are then sealed off in the ordinary way, and are ready for use.

CHAPTER VII.

ARC LAMPS.

IN arc lamps, as we have already stated,* the resistance which converts the current into heat is that of the heated air between the ends of two carbon rods, from one to the other of which the current passes. The light is produced by the incandescence of the end of the carbon poles and of the minute particles of carbon which become detached, and float in the heated air between them. The heated air containing the particles of carbon forms what is called the "electric arc."

The carbon rods vary in diameter from $\frac{1}{8}$ inch in the smallest lamps made, to $3\frac{1}{2}$ inches in a lamp recently constructed by the Brush Company.

The carbon rods slowly burn away, and therefore have to be continuously fed forward by suitable machinery, so as to keep "the resistance of the arc" as constant as possible. On the steadiness of the feeding machinery, and on its sensitiveness to minute changes in the resistance, depend in a great measure the steadiness and freedom from flickering of the light.

It is also necessary that all arc lamps should light themselves when the current is started, i.e., that when no current is passing, the carbons should be in contact, and that when the current commences to flow, they should be instantly separated to a distance giving an arc of the required resistance. This distance will vary according to E.M.F., size of lamp, &c., from $\frac{1}{16}$ inch to $\frac{3}{4}$ inch.

An immense number of regulators have been constructed

* Page 9.

by different inventors, but they may all be divided into some three or four general types. I propose in the present chapter to describe some three or four lamps only, selecting those which are in actual commercial use, and which differ as widely as possible among themselves.

The qualities required in lamps are different according to the service for which they are intended.

For lighthouse work it is absolutely necessary that the light shall never be extinguished for an instant, and that the mechanism shall be strong, and that an ordinary light-keeper shall be able to manage it. Expense, weight, and bulk are matters of no consideration whatever; neither is there any objection to the mechanism being below the arc, as the light is not required to be directed vertically downwards. Slight pulsations in the light are not a serious defect. The arc must always be kept in the focus of the reflector, so both carbons must be fed forward.

In lamps intended for street lighting the chief consideration is steadiness and freedom from flickering. They must be moderately cheap, and not too heavy to hang on an ordinary lamp-post. The whole of the mechanism must be above the light, so that shadows may not be cast downwards.

A temporary extinction of the light, though much to be deprecated, would not, as in the case of the lighthouse lamps, be likely to have consequences fatal to life, and therefore strength of machinery need not be studied to the exclusion of all considerations of economy.

Further, street lamps must be so constructed that several can be worked in one circuit off one machine, and so that the accidental extinction of one shall not affect the rest. As a slight lowering of the position of the light is not objectionable, one carbon may be fixed and only one fed forward.

Arc lamps are not suited for the interior illumination of rooms, but when so used considerations of perfect freedom from flickering outweigh all others. In this case the lamp must be also so adjusted as to be free from the hissing sound which is often produced by an electric arc.

All lamps should be constructed so that they will burn from dark to daylight of a winter night, say sixteen hours, without attention or requiring new carbons.

When lamps are worked by a direct current, the positive carbon consumes away about twice as fast as the negative; with an alternating current the consumptions are of course equal. The adjustments of springs, &c., required when direct and alternating currents are used, is somewhat different, as we shall see later on.

The principal regulator lamps at present in use are—the Serrin (used exclusively for lighthouses), and the Crompton, Brush, and Siemens (used for lighting streets, stations, and large buildings).

The Jablochkoff candle may be noted as a type of a class of arc lamp where the length of the arc is kept constant, but not its resistance.

The Serrin Lamp. (Plate X.)

Plate X. is a drawing of a Serrin lamp.

The base of the lamp contains clockwork, which is actuated by the weight of the upper carbon. The racks carrying the upper and lower carbons are connected by cog-wheels, so that as the upper carbon sinks the lower one rises to meet it. When the lamp is to be used with alternating currents the cog-wheels gearing into the two racks are of the same size, and the carbons advance equally. When direct currents are to be used, the cog-wheels are so proportioned that the + carbon moves twice as fast as the − one. As the carbons move, the star-wheel, which is the last wheel of the train, revolves very rapidly, and a very slight brake applied to it is sufficient to lock the carbons. When the carbons are in contact a current can be sent through the lamp. The current passes through the electro-magnet, which attracts its armature, and pulling a lever draws down the lower carbon-holder, and, separating the carbons, forms the arc. At the same time the lever locks the star-wheel, and prevents the carbons from moving.

As the carbons burn away the arc gets longer, and as its resistance increases, the current in the magnet gets weaker,

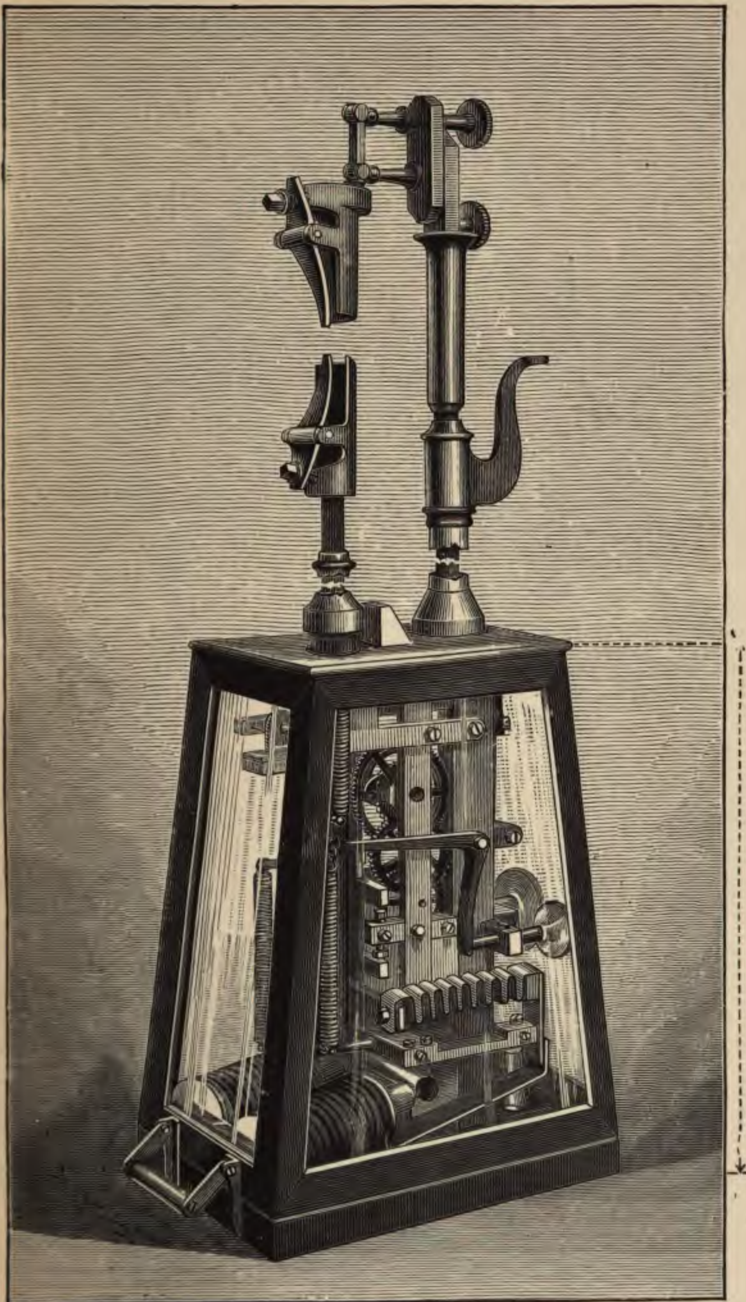


PLATE X.—SERRIN'S ARC LAMP.

PLATE XI.—CROMPTON'S ARC LAMP—OLD PATTERN.

and the armature is drawn a little way from it by the spring. This releases the star-wheel, and the carbons approach each other till the current has recovered its proper strength, when the armature is again attracted and the carbons locked. This adjustment is repeated at intervals until the carbons are consumed.

The upper carbon can be brought exactly into line with the lower one by means of the screws seen at the top of Plate X. Of the two screws seen on the left-hand side of the clock-case, one adjusts the tension of the spring and so regulates the length of the arc, the other enables both carbons to be raised or lowered together without altering their distance apart, so as to place the arc exactly in the focus of the reflector. The position of the arc should be level with the top of the little bracket which is pivotted on the tube inside which the upper carbon-rack slides. The bracket can be turned round so as to be close to the arc, or can be turned back out of the way. The lamp is simply slid into position on two brass rails, to which the wires from the machine are attached. In case of any accident to the lamp it can be removed and a spare one substituted in a few seconds, as placing the lamp in position at once makes the connections.

The Crompton Lamp. (Plates XI. and XII.)

Plates XI. and XII. and figs. 48, 49, are diagrams of three successive developments of arc lamps introduced by Messrs. R. E. Crompton and Co., of Chelmsford.

Plate XI. shows the first form, which was invented by Mr. Crompton in 1880, and was an improvement on a still earlier lamp, which it is unnecessary now to describe. In this lamp, which Mr. Crompton calls the E pattern, the lower carbon-holder has an up-and-down play of about ¼ inch; it is pressed up by the spring S, and is pulled down whenever a current passes through the magnet M.

The upper carbon-holder has a play of about 16 inches. When drawn up to its highest position it tends to sink slowly by its own weight, actuating as it falls a train of wheel-

work, which causes the little wheel E to revolve with great velocity. A very slight pressure on the rim of this wheel will stop the motion of the carbon. This pressure is generally maintained by a light spring, which presses on the wheel except when the lever N is lifted by the passage of a sufficiently powerful current through the magnet G.

The magnet G is wound with fine wire, and is of high resistance, and is connected so as to form a shunt to the arc. The magnet M is wound with thick wire, and is in the main circuit.

When a current is sent through the lamp, the carbons not yet being in contact, no arc is formed, but the whole current passes through the shunt magnet G, which lifts the brake-spring, and allows the upper carbon to descend until it comes in contact with the lower one.

The greater portion of the current then leaves the shunt magnet, releasing the brake and stopping the motion of the upper carbon, and passes through the carbons and through the thick-wire magnet M. This magnet depresses the lower carbon-holder about $\frac{1}{4}$ inch (the exact amount of play to be allowed having been previously regulated by a set-screw), and, separating the carbons, forms the arc.

The carbons being held in this position commence to burn away, until the length, and therefore the resistance of the arc, begin to exceed their proper limits. When this occurs a larger fraction of the current passes through the shunt magnet G, and, the brake being lifted, the upper carbon sinks. As the upper carbon approaches the lower one the resistance of the arc diminishes, and the current in the shunt magnet G diminishing, the brake again presses on the wheel E, and stops the motion of the carbon; and this adjustment goes on continuously until the carbons are consumed. We note that the adjustment depends only on the relative resistances of the arc and of the shunt magnet, and is not affected by variations in the total current. The only effect of a decrease of the current is to cause the lamp to burn with a shorter arc.

The special feature which distinguishes Mr. Crompton's lamp from the numerous other lamps in which a train of

wheelwork and a brake had previously been employed, is the extreme lightness and delicacy of the brake-spring and its adjustments, the whole of the moving parts weighing only a few grains.

When the brake-lever is heavy the adjustment of the arc does not take place until there has been a considerable increase in its resistance, and then the carbon is not again stopped until the arc has become too short; and in consequence, the light is constantly pulsating. With the light spring introduced by Mr. Crompton the adjustment takes place almost as the resistance begins to vary. In fact, with a Crompton lamp in good adjustment the wheel E is never quite still; the varying pressures of the brake simply appear to adjust the velocity of its motion. In consequence, the Crompton light is extremely steady.

The K pattern Lamp. (Fig. 48.)

Fig. 48 represents the lamp, brought out in 1882, known as the K pattern, and is the joint invention of Messrs. Crompton and Crabb.

In this lamp it will be seen that the frame carrying the wheelwork is made capable of motion in a vertical plane about a pivot fixed to the opposite guide-rod. Hanging vertically from this frame and within a solenoid, is a hollow cylindrical iron core. The solenoid, which does the work of the electro-magnets in the former lamps, is differential, i.e. it is partly excited by the current in the main circuit which passes through the lower and thicker wire, and partly by a small current circulating in the upper and much thinner wire which is connected as a shunt to the arc.

Attached to the upper or positive carbon-holder is a cord which passes over a pulley connected in the top of the frame, round another pulley connected to the train of wheelwork, and which corresponds to the toothed wheel gearing into the rack rod in the older forms of Crompton lamps; then down the hollow side rod, through one half of the cross-bar at the bottom, down the vertical tube, under a pulley attached to the lower carbon-holder, up the tube

on the other side, to the other half of the cross-bar, where it is fixed. The lower carbon moves up and down in the bottom tube, guided at its lower end by a piston-shaped socket, which makes good spring contact with the tube, and at its upper end by the nozzle at top of the tube, and is supported by its pulley, which sits in the loop formed by the passing of the string from one side of the cross-bar down and up the tube to the other side.

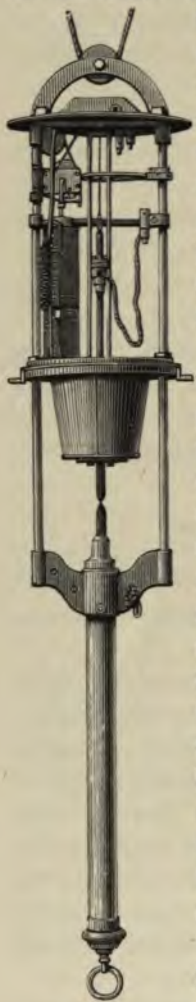


Fig. 48.

It follows from this arrangement that a downward motion of the solenoid's core produces an upward one of both carbon points; also that the positive carbon moves twice as fast as the negative one, and that the arc is maintained always at the same height. From the different rates of motion of the two carbons it follows that a drawing down of the core separates them, and its rising allows them to approach. Projecting from below the frame carrying the wheel-work is seen the brake-wheel, beneath and close to which is the brake, a thin strip of brass, which, when the frame has fallen a certain space, is caught by a projection on the side rod and prevented from moving down further with the frame, thus pressing on the wheel.

The action of the lamp is as follows:— On closing the circuit the carbon points which were before in contact are separated by the drawing down of the core consequent upon the action of the current in the main coils. This also allows the brake to press on the brake-wheel, and prevents the carbons from running together. The differential action of the two currents circulating in the coils of the solenoid, i.e. the main one through the thick wire, and the shunt current through the fine wire, causes the arc to adjust itself to the proper length. When this from any cause is ex-

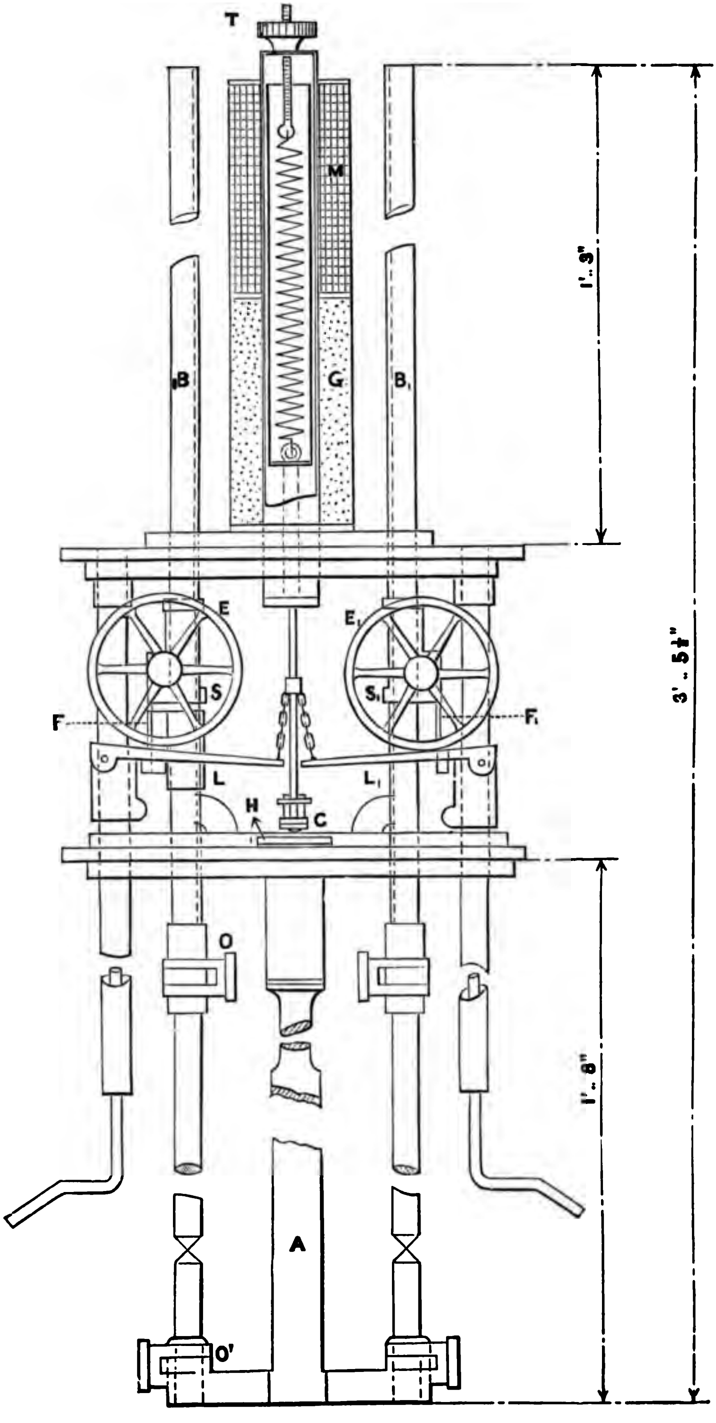


PLATE XII.—CROMPTON'S ARC LAMP—NEW PATTERN.

ceeded, its increased resistance throws more current through the shunt coils, the core is raised, the brake-wheel liberated, and the carbons approach. If the arc should be too short, then, the shunt current being diminished, this core is pulled down and the arc lengthened.

THE D. D. LAMP. (Plate XII. and fig. 49.)

The latest type of lamp made by Messrs. Crompton and Co. is known as the D. D. (double differential) lamp. It also is the joint invention of Messrs. Crompton and Crabb, and shows a marked improvement on the older forms in point of simplicity of construction and also in regulation. This latter is effected by a brake-wheel driven by the rack rod attached to the upper carbons, as in the 1881 pattern, over which, however, the D. D., in common with the K. lamp, possesses the great advantage of being able either to increase or decrease the length of arc as may be necessary, whereas the older lamp could only decrease it.

In the D. D. lamp also the intermediate gearing between the brake-wheel and the pinion driven by the rack rod is dispensed with. Referring to Plate XII., B and B_I are the rack rods carrying the positive carbons. Sliding on each of these is a light gun-metal sleeve, S S_I, carrying spindles, to which are attached the two large brake-wheels E E_I, and between them the pinion which gears into the racks. To each side rod is pivotted a broad lever, L L, at the other end of which a chain is fastened, connecting it to the hollow core of the solenoid vertically above. This solenoid is differential, as in the K lamp, G being the shunt and M the main coil, and has its core partially supported by a spring whose tension can be regulated by means of the screw T. Projecting vertically downwards from each sleeve to a distance from the centre of the spindle about equal to the radius of the brake-wheels, is a stout pin or finger, F F_I, the use of which we will try to make clear. Suppose the rack rod to be drawn up; then, if the lever be pulled by the solenoid above the horizontal position, the whole weight of the rod and carbon is supported on the edges of the two brake-wheels, and the friction of them on the surface of the levers is sufficient to prevent their revolu-

tion; hence this rack rod cannot run down: but if the levers be below the horizontal, then the weight is carried by the finger projecting from the sleeve, as shown at F, the wheels are free to turn, the rack runs down, and continues to do so until the positive and negative carbon points come in contact. Now let the current be switched on: by its passage through the main wire of the solenoid, the levers are raised, striking the arc, and at the same time applying the brake to the wheels. The shunt current then flows, and the arc takes its proper length. If this becomes too great, the increased current through the shunt draws down the core and levers; the brake-wheels are left free to revolve if the arc shortens.

On the other hand, if the carbon points be too close, the levers are raised, bringing with them the rack rods and upper carbons. Making the finger projecting from one sleeve longer than that from the other, determines which pair of carbons shall begin to burn first, because, on switching on, that pair which has the longer pin will be the last to break contact, and will therefore originate an arc in so doing. It will be easily seen from Plate XII. that on the core being raised the lever L_I will apply the brake before the lever L does, hence it may be said that the rack rod B_I gets a start on B; its carbon points are separated before those of B, and are kept a greater distance apart until the latter are consumed. When this is the case, the rack rod B_I is prevented from further fall by a stop and can no longer feed, hence the arc will lengthen, the shunt current will increase, and the other rod B_I, which can still feed, will be allowed to descend until its carbons touch, starting a fresh arc. The core is raised again, the fresh arc burning instead of the old one, and everything goes on as before.

When the second pair of carbons has burned low, the same action takes place, viz. further descent of the rod is prevented, the arc lengthens, the shunt current increases, and the core is drawn down, but lower than when the first pair of carbons were burned out, until a copper stud, C, attached to it makes contact with another, H, connected to the negative pole, cutting the lamps out of the circuit and introducing an equivalent resistance.

The connections of the lamp and its equivalent resistance coil are shown in fig. 49. The current entering in the direction of the arrow finds two paths open, the one through the resistance coil R R and insulated contact piece C, which for the time being is resting upon H, and thus on to the next lamp; and the other through the switch S, which we suppose to be closed, the main solenoid, coils M, the framework of the lamp, the positive carbon, the negative carbon, and

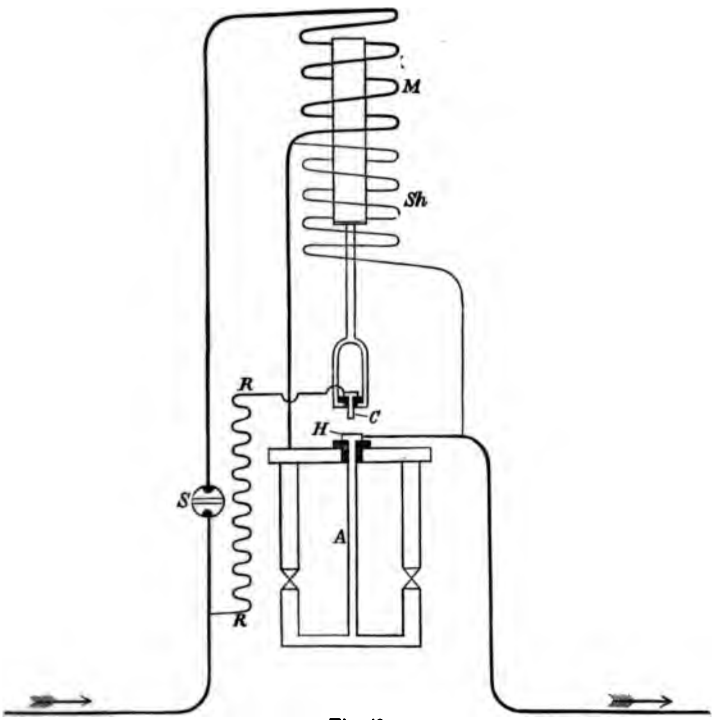


Fig. 49.

ultimately out by H, and on to the next lamp. The latter portion of the current in passing round the core magnetizes it and draws it up, thereby breaking contact between C and H.

In this moment the current has only one path open, viz. that through the switch S, main solenoid, and carbons; and since the whole of it must pass through the main solenoid, the core of the latter is definitely drawn up, lifting the two

rack rods, and establishing the arc between one pair of carbons as explained above.

If, through the falling out or breaking of a carbon or hanging up of the rack rods, the current should be interrupted, then the core of the solenoid will instantly fall, and, by bringing C and H again into contact, open to the current the former path through the resistance coil. In this manner an accident to one lamp does not affect the other lamps burning in series with it on the same circuit.

The same result will follow if the current be interrupted through the opening of switch S, and the lamp thereby be switched out of circuit.

When fitted with the full length of 19½ inches of carbon 13 m.m. in diameter, the lamps will burn from 12 to 16 hours, according to the current passing, which may vary from 6 to 28 ampères, the light varying from 850 to 6500 candles.*

The electro-motive force required is 50 to 60 volts.

Adaptation of the Crompton D. D. Lamp to Alternating Currents.

On trying the above lampwith alternating currents, I found that at first it did not burn satisfactorily. An examination of the currents circulating in the different parts showed the curious fact that the current in the shunt coil, instead of varying inversely as the current in the main wire, varied *directly* with it, and of course the lamp did not regulate.

The reason of this was that the coils of thick and thin wire, having a long iron core common to both, acted like an induction coil, and the alternating current in the thick wire induced currents in the fine wire, whose strengths were of course proportional to its own strength, and which quite overpowered the shunt current.

To get over the difficulty, I cut the core into two halves, and connected them by a brass rod equal in length to one of the halves. I then turned the coils over so that the thick

* The above candle-power being measured at an angle of 30° below the horizontal line cutting the arc itself.

wire coil was at the bottom and the thin at the top (fig. 50). A comparison of figs. 49 and 50 shows the nature of the alteration.

On again trying the lamp, I found that the induction coil effect had ceased, and that the lamp regulated perfectly.

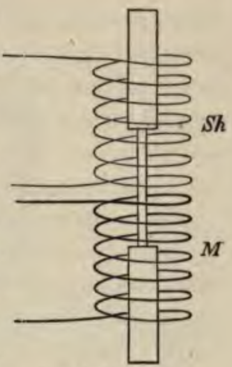


Fig. 50.

MOUNTING.

Fig. 51 shows a Crompton lamp mounted in an ornamental case.

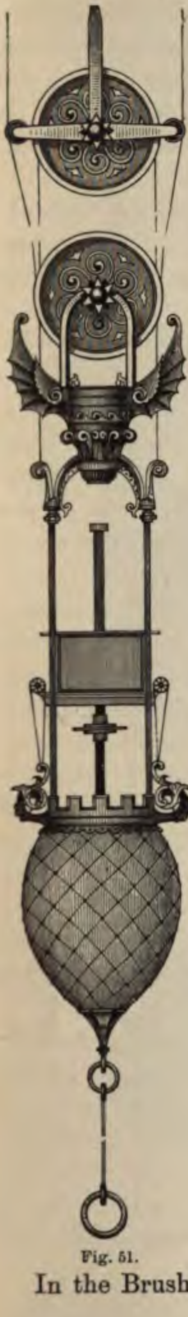


Fig. 51.

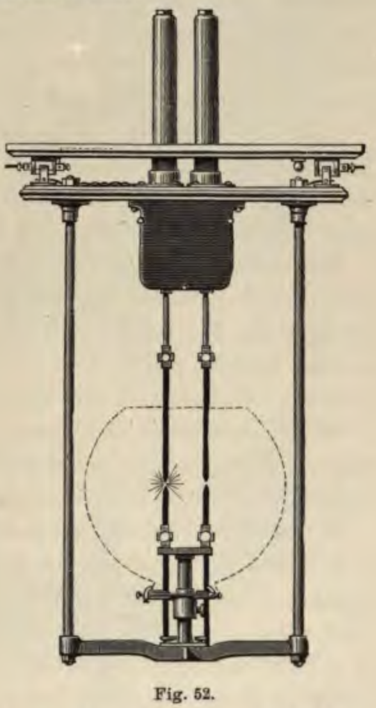


Fig. 52.

THE BRUSH LAMP. (Plate XIII.)

In the Brush lamp, shown in Plate XIII. and in fig. 52,

there are also two pairs of carbons, and the mechanism is so arranged that when the current is started the arc is formed between one pair, which continue to burn till they are consumed, when the current is instantly transferred to the second pair. This lamp therefore can also be made to burn all night without having very long carbons.

The small magnet seen in Plate XIII. works a "cutout" similar in principle to that already described in the Crompton lamp. The large magnet both makes the arc and regulates the descent of the carbon.

The magnet is wound with two wires, a thick and a fine one. The thick wire is in the main circuit, and the fine wire forms a shunt to the arc. The wires are so connected that the currents in them circulate round the magnet in opposite directions, so that the strength of the magnet depends only on the difference between the main current and the shunt current. The action of the main current being made the more powerful of the two, the main current tends to increase the magnetism, and the shunt current to decrease it.

The cores of the magnet are tubular, and two iron bars are attached to the armature, which are sucked into the magnet as the current gets stronger. This arrangement enables a play of some two inches to be given to the armature.

When the armature is raised it lifts the upper carbons by means of the clutch shown in detail at the bottom of Plate XIII. Each of the sliding rods carrying the carbon passes through a loose washer, which does not grip it as long as the washer is level. One side of the washer enters a notch in a strip of brass attached to the armature. When the armature is raised, one side of the washer is lifted by it, and the washer, being tilted, grips the rod, and lifts the carbon with it.

In order to avoid sudden jerks, a cylinder full of glycerine is attached to the armature, and a piston working in it is fixed to the upper part of the lamp, as shown in Plate XIII. The armature is thus compelled to move slowly and smoothly. A similar arrangement is applied to the carbons. The rods carrying them are made tubular and filled with glycerine, and pistons are fixed to stout wires at the top of the tubes seen in Plate XIII.

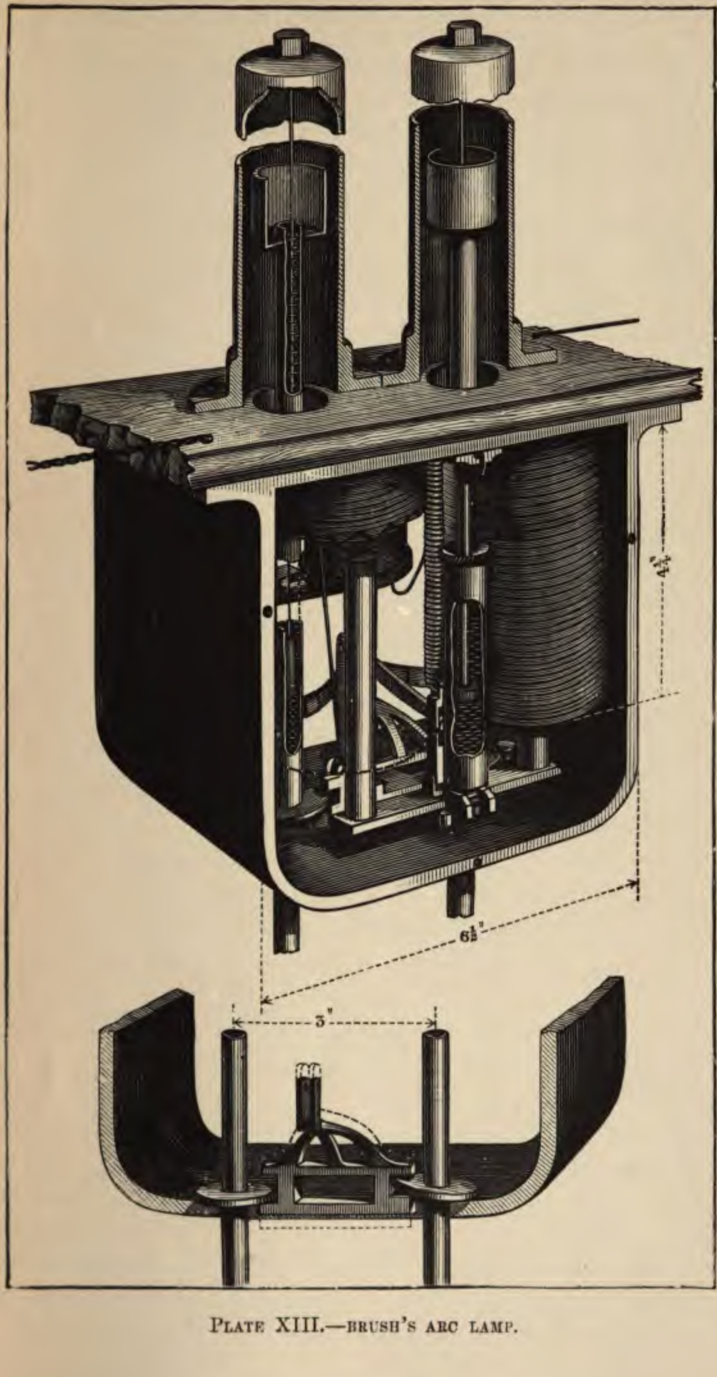


PLATE XIII.—BRUSH'S ARC LAMP.

Before the current passes, both carbons sink till they are in contact with the lower carbons. When the current commences it at first passes partly by the "cut-out," and partly through the magnets and carbons. The "cut-out" magnet breaks the short-circuit, and the whole current passes by the magnets and carbons. The main current being much stronger than the shunt, the armature is lifted, raising both carbons.

A reference to Plate XIII. shows us that the lower edge of the left-hand slit is at a higher level than that of the right-hand one. The right-hand carbon is therefore less raised than the left-hand one, and the arc forms itself between the right-hand carbons.

As the resistance of the arc increases, the main current, which tends to magnetize the magnet, diminishes, and the shunt current, which tends to demagnetize it, increases, and so the magnetism diminishes, and the armature sinks. As soon as it has sunk a little, the right-hand washer becomes level, and allows the carbon-holder to slip through it. The arc becoming shorter, the power of the magnet increases, and the armature is raised, and the carbon again locked.

During this adjustment the armature never sinks far enough to release the left-hand washer. The adjustment is repeated at short intervals until the right hand carbon is consumed, say in about eight hours from the time when the lamp was lighted.

When the carbon is consumed the holder is stopped by a collar, and the current through the carbons ceases for an instant, and the cut-out armature falling, the lamp is short-circuited.

The left-hand carbon then instantly falls, and comes into contact with its lower carbon. The circuit through the lamp being re-established, the cut-out armature is again lifted, the carbon is raised so as to form a new arc, and the regulation goes on in the same manner as before until the second carbon is entirely consumed. At the instant of change of the current from one pair of carbons to the other the lamp is extinguished for something less than a second.

The ordinary lamps used for street lighting burn carbons of 9 millims. diameter, and are said to use 10 ampères of

current, and to require an E.M.F. of about 50 volts. The H.P. consumed in them would be, by equation (7),—

$$\text{H.P.} = \frac{50 \times 10}{746} = \cdot 67.$$

These lights are probably of about 800-candle power.

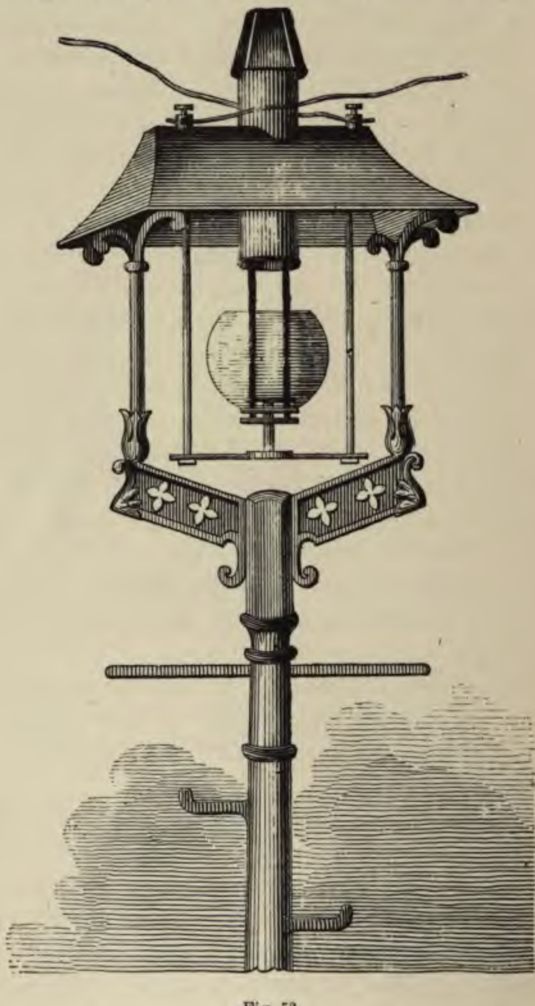


Fig. 53.

The Brush Company have been very successful in working a large number of their lamps in series on one circuit. Forty on one circuit are in regular use in Cheapside.

Fig. 53 represents a Brush lamp mounted on a street lamp-post.

Brush lamps are also made with larger carbons, taking more power. One has been constructed with carbons $3\frac{1}{2}$ inches diameter, requiring 40 H.P., and giving a light said by the company to be equal to 150,000 candles. This is by far the largest electric lamp of any kind which has yet been made.

The Jablochkoff Candle.

In the Jablochkoff candle (fig. 54) the two carbon rods are placed side by side, and are separated by a strip of plaster composed of kaolin and other ingredients.

The current passes up one carbon and down the other, and the arc is formed at the top. The whole burns downwards like a candle. The candles are tipped with a paste made of powdered carbon and gum. When the current is first started it passes through this paste, which, becoming incandescent, rapidly burns away, and leaves an arc formed between the poles. In case of the current being accidentally interrupted for an instant, the candles go out, and do not re-ignite themselves.

In the Jablochkoff candle the length of the arc remains constant, but its resistance is constantly varying with every impurity or change of density in the plaster. The light is therefore extremely unsteady. The extreme simplicity of the Jablochkoff candle, and the absence of machinery, are however a certain recommendation to it. It is of considerable historical interest, as the lighting of the Avenue de l'Opera in Paris in 1878 by Jablochkoff candles first demonstrated the possibility of street lighting by electricity.

The Jablochkoff candle can only be used with alternating currents, as it is necessary that the carbons should consume equally.

Fig. 45.

CHAPTER VIII.*

CARBONS FOR ARC LAMPS.

DAVY'S first experiment with the electric arc was carried out with pieces of wood charcoal as electrodes, but it was at once seen that electrodes formed of such a soft material could not be of much practical use, as they burned away too rapidly, and gave off coruscations of dangerous sparks. It may be here mentioned that, seventy years later, Gaudoin, at Paris, again reverted to the use of rods of wood charcoal, the density of which he increased to any required extent by filling up the pores with various hydro-carbons, alternately soaking the rods in liquid hydro-carbon, and firing them until they gave a metallic ring. But for many years the carbon electrodes used for all experiments with the electric light were strips sawn from the graphitic deposits found in gas retorts. Foucault has the credit of introducing these.

The carbon electrodes as now used are the result of the experimental researches of Staite, Laccasagne, and Thiers, Archereau, Carré, Gaudoin, and others. Most of the makers observe a certain amount of secrecy in regard to their processes of manufacture, but the general features of it are well known to be as follows :—

Coke or graphite is finely powdered and washed in alkaline cells to get rid of the silica and earthy impurities, after which it is ground in a pug-mill, with sufficient syrupy or tarry hydro-carbon to agglutinate it into a stiff paste. This paste is then pressed into rods of the required form by being forced through moulds or dies.

* I have to thank Mr. Crompton for this chapter.

Sometimes the pressure is applied endways, the paste being forced out in a continuous rod of the proper thickness, and cut off into lengths as required. Another plan is to apply the pressure sideways, the dies being divided longitudinally into two parts. In the latter case, several rods are usually pressed at one time. The rods thus formed are carefully dried, and afterwards fired in kilns, having been previously packed in air-tight boxes, and embedded in coke dust. After one firing they are generally found to be porous, and require soaking in syrup and a second time firing. Some of the makers repeat this process more than once.

The manufacturers who during the last few years have done most to perfect carbon electrodes have been—Carré, Sautter-Lemmonier, and Mignon-Rouart, in France; Siemens in Germany; Gray, Hedges, and Johnson and Phillips in England.

The following points are aimed at in the production of a perfect carbon for arc lighting:—

1. Freedom from all matter other than carbon.
2. Regularity of density.
3. Mechanical perfection of form.
4. Low electrical resistance.

Purity.

It is not sufficient that the coke or other powdered carbon from which the rods are made should be in the first instance free from earthy or metallic impurities, but a great deal depends on the care taken in subsequent processes of manufacture to insure that the volatile gases, most of them hydrocarbons, are thoroughly expelled during the process of firing. The reasons for this are as follows:—

Carbon being the most refractory of any known substance, disintegrates to pass across the arc at the highest possible temperature, and as the whiteness of the colour, as well as the amount of the light given by the electric arc, depends entirely upon the temperature of the arc, it is evident that any admixture of substance other than carbon will, by lowering the mean temperature at which the electrode is disintegrated, tend to diminish the amount of light given.

Observations taken with the spectroscope show that at the times when the arc distils itself free from all foreign salts, so that we have in the spectrum only the characteristic carbon lines, the colour of the light is most intensely white, and the amount of light is at a maximum; and it is almost certain the temperature is also at a maximum. At the same time it is observable that the conductivity of the stream of matter passing across from one electrode to another is at a minimum, hence if the difference of potential at the two sides of the arc is maintained constant, the arc will be shortest at the times that the carbon is purest, and the action being then confined to the smallest possible space, will be intensified in proportion, resulting in greatly increased light and economy. The addition of the smallest portion of any material which volatilizes at a lower temperature than carbon itself, increases the length of the arc with the results the reverse of those above mentioned.

Gaseous impurities, the chief offenders being hydrocarbons, are peculiarly annoying in this respect. When they are present to any extent, they always break out at irregular intervals as blowers of gas, which are comparatively of high conductivity. These jets play around the crater proper in a most irregular manner, and are the chief cause of the flickering so often complained of in arc lighting. It is quite common to see the arc start from a point very high up on the cone outside the crater, and forming a curved and rapidly-moving jet towards a point on the cone of the negative carbon. At such moments the light is found diminished to one-third or one-quarter of its normal brilliancy, and as the lamp adjusts itself to the new conditions by automatically lengthening the arc, a vibratory or reciprocating action is set up in the lamp, which greatly intensifies the mischief.

Silica and other earthy matter when present in carbon, in addition to lowering the arc temperature, form a more or less bulky ash, which falls down into the surrounding globes, and is extremely unsightly. When continuous currents are used, this ash accumulates on the negative electrodes, and thus produces ugly and otherwise objectionable shadows.

Regular Density.

This has been attained much more perfectly of late years since the introduction of dies split longitudinally, so that a side pressure equal in extent throughout the full length of the rod can be applied. Rods made by end pressure very frequently have the ends more or less dense than the middle portion; consequently, when such rods are used, the lamps burn quite differently when first started, and when the carbons are nearly burned out.

A defect, which shows itself more particularly with carbons used for continuous currents, and which probably is due to irregularity in density, is that the point of the positive carbon, instead of forming itself into a crater of regular concavity, forms a number of small craters or facits inside one general crater. This irregularity is always accompanied by noise and unsteadiness when burning.

It seems as if, although the density of the rod may be fairly regular throughout, yet that the whole is made up of a honeycomb of dense carbon filled in with softer carbon, the action of the current being, as it were, to excavate the soft carbon, leaving the hard carbon ridges prominent.

Carré, Siemens, and others have attempted to get over this difficulty by purposely varying the density of the rod. That is to say, they have put a soft core into a hard carbon, so that the current itself would always excavate the soft core slightly in advance of the hard carbon exterior. This insures that the crater be kept truly concentric with the rod, and certainly it has given the desired effect. Otherwise this defect of irregular local density could be got over by increased care in the grinding and pugging of the carbon paste prior to the pressing.

Mechanical Perfection of Form.

Little need be said on this head. It is evident that modern requirements, which insist on arc lamps burning for many hours at a stretch without renewal of the electrodes, necessitate long rods, and these must be perfectly cylindrical, of equal diameter throughout, and perfectly straight.

The longer the rods are made, the more difficult it is to preserve their straightness through the many processes of drying, firing, soaking, &c.

Some of the densest, purest, and most regular carbons in the market are great offenders in this respect, and consequently are quite useless for long burning lamps. If the rods are not perfectly cylindrical and of equal diameter throughout, it is very difficult to make good contact with the carbon-holders, and as a result the carbons heat at the point where they are nipped by the holders, even to such an extent as to char away, and thus become loose and fall out. Any irregularity at this point makes it next to impossible for the attendant changing the carbons to get the two rods into line with each other.

Electrical Resistance of Carbon Rods.

This is a matter of greater importance than might be at first imagined. When many arc lamps are burned in series, if the electrical resistance of the carbons themselves is high, it becomes a serious matter to deal with. For instance, with forty arc lamps in series, the resistance of the carbon rods only, when the whole of the lamps are newly replenished, will be, under the most favourable conditions, twenty ohms, and this becomes reduced to two or three ohms when the rods are burned down short.

The purest and densest carbons are also found to have the lowest resistance, but in such a case as that above mentioned, or in fact wherever more than sixteen lamps are used in series, it is found necessary to reduce the resistance by electro-plating the carbons with copper or nickel. This copper-plating presents serious disadvantages; one of them being that, when direct currents are used, the copper on the negative rods is not burned away under the action of the arc as fast as the carbon itself. It therefore stands up in the form of a ragged fringe round the negative rod, which throws a large star-shaped shadow on the floor beneath. It is also believed that the volatilized copper which is always present in the atmosphere when copper-coated carbons are used, although harmless in the open air, would be dangerous to health in confined workshops. Hedges succeeded in

plating his carbons with iron, which in one way got over this difficulty, but he met with a fresh one, for it was impossible to keep the covering from rusting unless it was protected with some varnish, which had to be scraped off at the point where the carbon entered the holder. De Hamel patented a process of inserting an iron wire up the centre of carbon rods, the idea being to diminish the resistance, it being also found that the volatilizing of the iron did not affect the colour of the light; but there is no doubt that, for the reasons above given, it lengthened the arc, and diminished its economical efficiency.

At any rate, this process has so far not proved an economical success.

The Size of Carbon Electrodes.

The economical efficiency on the one hand, and the steadiness of the light on the other, depend very greatly on the diameter of the carbon electrode employed with a given current. Within certain limits the one is in inverse ratio to the other. That is to say, as we decrease the diameter of the carbon, we increase the amount of light from a given current, and decrease its steadiness. The diameters most commonly used have been as follows:—

For currents from	7—12 ampères	9 m.m.*	to	11 m.m.	diam.
„	12—18 „	11 m.m.	„	13 m.m.	„
„	18—25 „	13 m.m.	„	15 m.m.	„
„	25—40 „	15 m.m.	„	18 m.m.	„
„	40 upwards	18 m.m.	„	20 m.m.	„

It is extremely difficult to obtain carbons above 20 m.m. of sufficient homogeneous texture to give a steady light with lamps having automatic regulation. All carbons above this diameter are used with the large arcs as search lights for military and naval purposes, and most commonly worked by non-automatic hand regulators, and as all the best modern projectors are fitted with an arrangement for viewing the arc from the side, the attendant in charge can quickly set right any irregularity caused by change of density.

If the above rules as to diameter proportionate to current are departed from, the following results take place:—

* One m.m. (millimetre) is practically equal to $\frac{1}{25}$ inch.

If a carbon of too small diameter is used, the positive carbon cores away so rapidly as to cut down the sides of the crater, and the intensely-heated portion of the carbon extends outside the walls of the crater proper; in this way a great amount of the light which ordinarily would be thrown downwards on to the surface required to be illuminated, will be wasted in the upper part of the spherical angle. In addition to this loss, there is great danger of the carbon becoming red-hot from end to end, and thus wasting away like a candle in a hot oven. Again, the light also becomes very unsteady; the arc does not pass steadily between the points of the cone and the crater proper, and the lamp burns for a shorter time than it ought to do.

On the other hand, if carbons of too great diameter are used, they do not point properly, and consequently, the angle of the lower carbon being very obtuse, throws down a large shadow. A great part of the electric energy, instead of being utilized in producing an intense temperature at the crater, is wasted in heating the external portion of the massive carbon to red heat.

Nevertheless there is no doubt that the use of large carbons has greatly extended during the last few years. Although energy is wasted, and consequently less light is afforded by a given current, there is a great increase in steadiness, and the lamps burning for longer hours do not require so much attention.

The following table gives the result of experiments on various carbons:—

ILLUMINATING POWER PER ELECTRICAL H.P. OF 13 M.M. CARBONS OF DIFFERENT MAKERS.

Currents from 15 to 20 Ampères.

Name of Maker.	Candle-Power per H.P.	Difference of Potential either side of Arc.	Remarks.
Siemens (cored) pos. / Carré (cored) neg.	4270	47·4	Mean of 4 Readings.
Siemens (cored) . .	3514	46·9	" 12 "
Barnsley Co. . .	3500	49·8	" 4 "
Johnson & Phillips .	2986	39·7	" 3 "
Sautter & Lemonnier .	2920	48·0	" 6 "
Carré (not cored) .	2773	45·1	" 6 "
Silvertown (Grays) .	2580	46·1	" 2 "
Carré (cored) . .	1972	42·8	" 5 "

Currents from 5 to 15 Ampères.

Name of Maker.	Candle-Power per H.P.	Difference of Potential either side of Arc.	Remarks.
Siemens (cored) pos. / Carré (cored) neg.	3564	54.0	Mean of 4 Readings.
Barnsley Co.	3010	54·2	„ 4 „
Silvertown (Grays)	2715	46·9	„ 2 „
Carré (not cored)	2650	40·75	„ 2 „
Sautter & Lemonnier	2442	48·0	„ 4 „
Johnson & Phillips	1820	39·75	„ 2 „
Carré (cored)	1667	46·2	„ 4 „

The current was measured by a Sir William Thomson Current Galvanometer.

The volts were measured by a Crompton-Kapp Potential Indicator.

The candle-power was measured by a Sugg's Patent Bunsen Photometer with a 100-inch bar and a 16-candle standard Argand Gas Burner.

The photometric measurements were taken direct from the arc, the lamps being inclined 30° from the vertical position, so that the measurements are equivalent to those taken 30° below the horizontal line

Illuminating Power per Electrical H.P. of Siemens' Cored Carbons of Varying Diameters.

Ampères.	18 m.m. Candles.	18 m.m. Volts.	13 m.m. Candles.	13 m.m. Volts.	11 m.m. Candles.	11 m.m. Volts.
5 to 14	2660	60·0	2278	48·0	2549	52·2
14 „ 18	4400	39·0	3514	46·9	—	—
18 „ 25	5263	42·75	3637	42·9	—	—

CHAPTER IX.

MAGNETS AND ELECTRO-MAGNETIC INDUCTION.

MAGNETS—PRELIMINARY NOTE.

MAGNETS are of two kinds, either steel "permanent magnets," which only differ in size and strength from the little magnets of the toy shops, or "electro-magnets," which consist of a core of soft iron wound with a quantity of insulated wire, and only become magnetic when a current of electricity is sent through the wire, the polarity and strength of the magnets depending on the direction and strength of the currents.

If the iron core of an electro-magnet is removed, the helix of wire when traversed by a current still exhibits magnetic properties, much feebler in degree, but the same in kind and direction, as those of the electro-magnet.

A coil or ring of wire carrying a current may therefore be regarded as an electro-magnet, whose polarity is the same as it would have been if an iron core had been inserted.

RELATION BETWEEN POLARITY AND DIRECTION OF CURRENT.

If in an electro-magnet we imagine a man to be swimming in the current down-stream and looking at the core, the north pole will be on his left hand.

By the north pole I mean the one which would repel the marked end of a compass-needle, or which would point northwards if the magnet were freely suspended in a horizontal position.

Electro-magnetic Attractions and Repulsions.

Magnetic poles of the *same* name *repel* each other, those of opposite names attract. Currents in the *same* direction *attract* each other, those in opposite directions repel.

If the force between the poles of two electro-magnets is repulsive, the force between their coils when the cores are removed is also repulsive, and *vice versâ.*

Let figs. 55 and 56 each represent two electro-magnets placed side by side.

In fig. 55 the poles are dissimilar and will attract, and we see that the currents in neighbouring wires are in the same direction, and therefore will attract also.

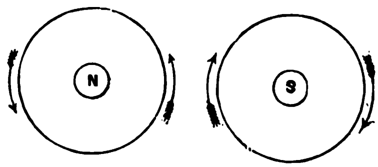


Fig. 55.

In fig. 56 the poles are similar, and the currents in neighbouring wires are in opposite directions, and therefore both poles and wires repel each other.

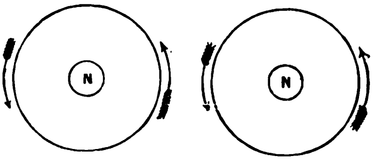


Fig. 56.

If in each figure we imagine the right-hand magnet to be turned over so as to face the left-hand one, we see that the forces will be of the same signs as before.

Lines of Magnetic Force.

Every magnet, whether it is a permanent magnet or an electro-magnet, or the imaginary magnet to which a coil of wire carrying a current is equivalent, may be considered as having *lines of force* emanating from its poles.

These lines of force never have a free end.

If a line of force starts from, for instance, the N. pole of a magnet, its other end must be in a S. pole somewhere. This S. pole may either be the S. pole of the same magnet, or a S. pole of another magnet, or a S. pole induced by the magnet itself in a neighbouring piece of iron. Thus the directions and curvatures of the lines of force of a

magnet are affected by any pieces of iron, or by any magnets that may be near it.

Magnetic Field.

The space round a magnet is called a *magnetic field.* The strength of a magnetic field may be conveniently expressed by the number of lines of force which pass through it. The strength of the field at any point may be expressed by the number of lines of force passing through a unit of area placed at that point. Thus, where the force is strong the lines of force may be said to be crowded together, and where it is weak to be thinly distributed. Just in the same way the density of a crowd at any point might be expressed by the number of people standing on a square yard of ground at that point.

We must bear in mind, however, that *the lines of force have no breadth, and that consequently there is no limit to the number that can pass through a given area.* This fact is of great importance in the construction of dynamo machines.

Magnetic Induction.

A magnetic pole at rest near a piece of soft iron induces an opposite pole to itself at the end of the iron nearest to it, and a pole similar to itself at the far end.

Experimental tracing of the Lines of Force of a Magnet. (Plate XIV.)

The direction of the lines of force of a magnet may be accurately determined, and the relative number which pass through each portion of the field may be approximately determined, by the following method :—

Let a stout, highly-glazed card be laid on the poles of the magnet, and let a few iron filings be dusted on to it from a sieve, the card being gently tapped during the whole time. The filings will arrange themselves along the lines of force, and will be thickest where the field is strongest, i.e. there will be a greater number of lines of filings where there are a greater number of lines of force.

If it is required to preserve the curves, a sheet of paper,

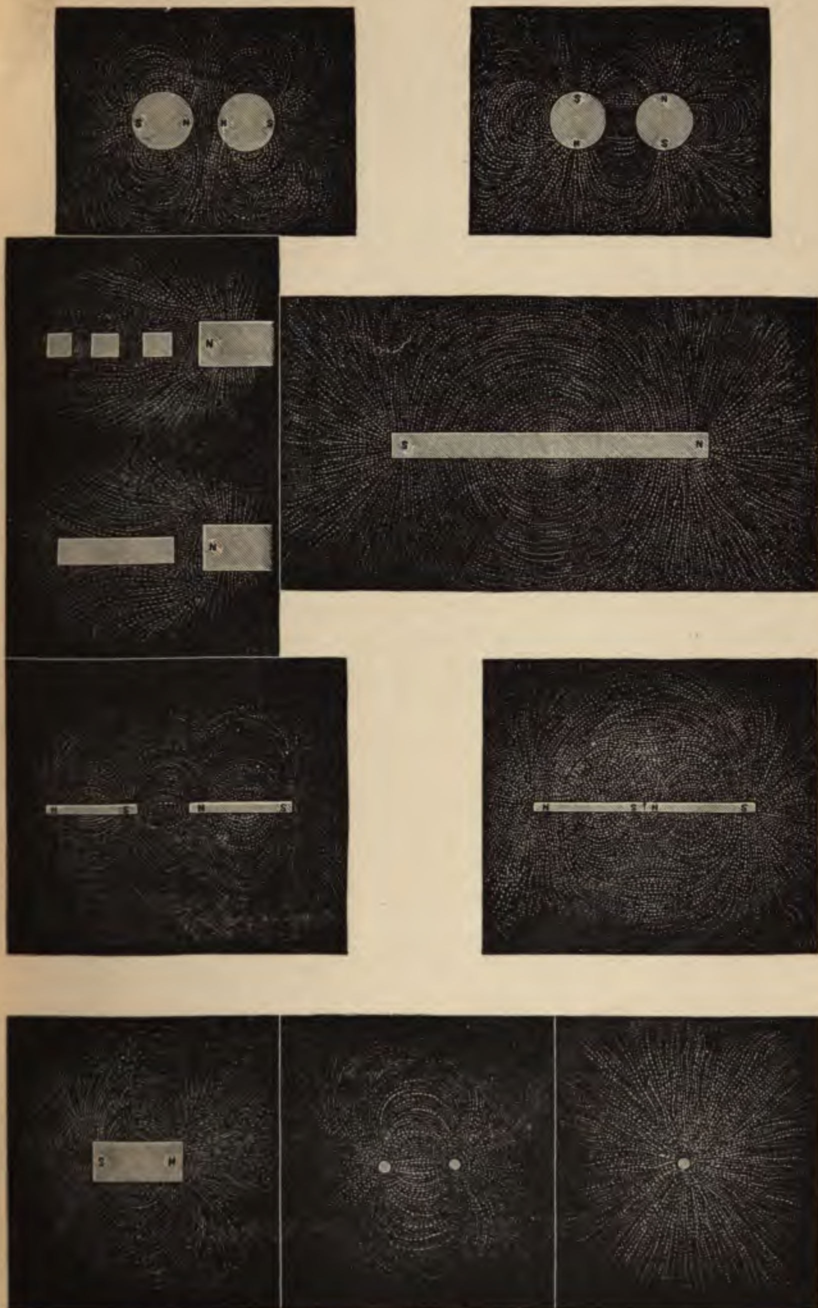


PLATE XIV.—LINES OF MAGNETIC FORCE.

with its under surface gummed, may be laid on them so that the filings may adhere to it.

Plate XIV. represents some lines of force determined by Faraday.

Another method of tracing out lines of force and measuring the intensity of magnetic fields depends on electro-magnetic induction, and will be described later on. See page 117.

Continuity of Physical Change.

All physical changes of whatever kind are continuous, i.e. if a body is in one state at one time and in another state at another time, we know that between those times it must have passed through all intermediate states.

For instance, if a body has a temperature of 10° at one time and of 20° at another time, then we know that at some time between those times it must have had a temperature of 15°.

As a corollary of this law we may note, that if any property of a natural body has at one time a (+) value and at another time a (−) value, then at some instant between those times its value must have been zero.

For instance, if a body is at one time above the ground and at another below it, then at some instant between those times it must have been at the ground level.

A careful remembrance of this law will save the electrical inventor from many mistakes and difficulties.

For instance, we must remember that if the N. pole of a core changes to a S. pole, then that at some period between the times when the pole had N. and S. polarity, it must have been completely demagnetized. Again, if a current is reversed, it must cease altogether between the times of its flowing in one and the other direction.

Electro-magnetic Induction.

If a wire be moved through a magnetic field, an electromotive force will be produced between its ends which will be simply proportional to the number of lines of force cut by it per second; lines cut in one direction being reckoned +, those cut in the other direction being reckoned

—, the sign being also reversed if the polarity of the field is reversed.

The number of lines of force cut per second depends,

First (in a uniform field), on the length measured in a straight line from one end of the moving wire to the other; i.e. if A B C., fig. 57 be the wire, it depends on the length A D C.

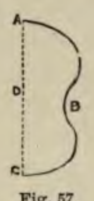


Fig. 57.

Second, on the angle which the direction of motion makes with the lines of force. If the wire moves along the lines of force, it will cut none of them; if at right angles to them, it will cut the maximum number. The number cut is directly proportional to the sine of the angle which the direction of motion makes with the lines of force.

Third, on the number of lines of force which pass through each unit of area of the region across which the wire moves, i.e. on the strength of the magnetic field.

Fourth, on the velocity of motion.

If the ends of the wire are connected by another wire not in motion, a current will flow through the wire, whose strength depends on the electro-motive force produced and on the resistance of the circuit.

For instance, the circuit may be completed by means of two fixed rails, on which the moving wire slides, the rails being connected at one end.

If in a uniform field the ends of the wire are connected by means of a second wire, which also moves across the lines of force (fig. 58), no current will be produced. The electro-motive forces in the two halves of the ring formed by the two wires will be in the same absolute direction in space, and therefore in opposite directions in the ring. In fig. 58 we suppose the lines of force to be perpendicular to the paper, and to be represented by the dots. We suppose the circuit to consist of a

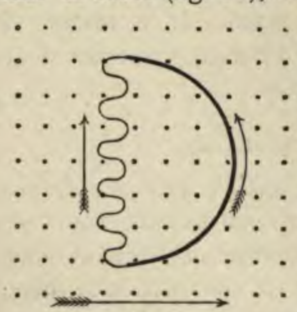


Fig. 58.

curved wire whose ends are connected by a zigzag one, and that it moves in the direction of the large arrow. We see that each half of the circuit cuts the same number of lines of force, and the electro-motive forces are both of the same magnitude, and are in opposite directions in the ring, as represented by the small arrows; and therefore there will be no current.

The moving of a wire across the lines of terrestrial magnetic force will produce an electro-motive force between its ends. A large portion of the earth's magnetic force is vertical; a horizontal wire moved parallel to itself will therefore cut terrestrial magnetic lines. Let us suppose the rails of a railway to be insulated from each other, but connected at one end through a galvanometer. The wheels and axle of a railway carriage would complete the circuit. As the carriage moves, an electro-motive force will be produced between the ends of the axle, which will produce a current through the galvanometer. If there are several axles they will all act in the same direction, like batteries in parallel circuit.

If, instead of being connected to the rails, the galvanometer, were connected to the ends of the axle, and carried in the carriage, no current would be produced, the reason being that equal electro-motive forces would be produced in the axle and in the connecting wires of the galvanometer. These forces would be in the same absolute direction, and therefore would be opposed to each other in the circuit.

Theory of Electric Generators.

All electric generators consist of machines for moving wires past magnets, or magnets past wires, the connections being so arranged that the electro-motive forces generated may produce currents.

If our moving circuit consists of a ring which is sufficiently large in comparison with the field, we can cause one side of it to move over the N. pole of a magnet while the other side is moving over the S. pole, and the electro-motive forces produced in the two halves will then be in opposite

directions in space, and therefore in the same directions in the ring, and currents will circulate.

Let us suppose our moving circuit to consist of the two axles of a four-wheeled railway carriage (fig. 59), connected

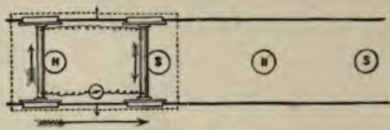


Fig. 59.

by wires running along the sides of the carriage, and passing through a galvanometer carried in it; and suppose that instead of making use of terrestrial magnetism, we bury in the permanent way a number of powerful magnets (fig. 59) of alternate polarity, the distance between the poles being equal to the distance between the axles. We see that the electro-motive forces produced in the two axles will be in opposite directions, and therefore a current will circulate until the axles arrive at the neutral point between two poles. The current will then diminish to nothing, and then gradually increase again; but as the field now being passed through by each axle is of opposite polarity to what it was before, the current will be in the opposite direction. And thus as the carriage moves on, currents will be produced which will be reversed in direction each time the centre of the carriage passes a pole.

The principle of this arrangement is the basis of all *alternating-current machines.*

We see, therefore, that the only way in which currents can be induced in a closed ring or coil of wire, is by the approach to or recession of the coil from a pole.

A motion through a uniform field produces equal and opposite electro-motive forces in the two sides of the coil or ring, which forces neutralize each other.

If the floor of the carriage in fig. 59 had consisted of a thick iron plate, the electro-motive force produced would have been greater, for the lines of force would have been nearly vertical, as in fig. 60, instead of partly horizontal, as in fig. 61.

In practice, the only way in which wires can be moved rapidly past magnets is by attaching them to the periphery of a revolving wheel round which stationary magnets are

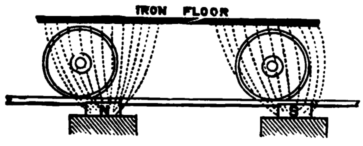


Fig. 60.

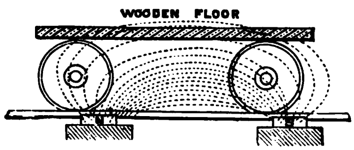


Fig. 61.

arranged, so that the wires pass the same magnets again and again.*

Another way of enabling the induced electro-motive forces to produce currents, is that invented by Professor Paccinotti in 1863, and known as the "Paccinotti or Gramme ring." By this apparatus the currents are produced continuously in one direction. Its principle is the basis of all *continuous-current machines*. We shall fully describe it in Chapter XIII.

Direction of the Induced Currents—Lenz's Law.

In 1834† Lenz enunciated the following remarkable law:—

Whenever a current is induced in a circuit by the relative motion of the circuit and of a magnet, or of another circuit carrying a current, the direction of the induced current is such that by its attraction or repulsion on the inducing magnet or circuit it opposes the motion.

We see that if this were not so we should have a "perpetual motion," as the induced current might produce the motion which itself produced the induced current.

Induction by Variation of Current in one of two Stationary Circuits.

If an electro-magnet, or a circuit (which may be regarded as an electro-magnet without an iron core) be placed near a

* Or the magnets may be attached to the revolving-wheel and moved past fixed wires.

† Pogg., Ann. xxxi. 483 (1834).

coil of wire, and the current in the electro-magnet be made to vary, currents will be induced in the circuit as long as the variation continues.

The direction of the current produced by increasing magnetism is the same as that produced by an approaching pole, that of the current produced by decreasing magnetism is the same as that produced by a receding pole. An increasing current in the electro-magnet induces a current in a direction opposite to its own; a decreasing current, one in the same direction.

Iron Core.

An iron core may be placed in the circuit in which a current is to be produced. This generally increases the effect as it strengthens and concentrates the lines of force.

As the directions of the induced current have a constant relation with the changes of polarity of the core, we may, if we please, study the latter instead of the former. The actions are somewhat easier to follow.

Effect of the Iron Core on the Coil surrounding it.

If the magnetism of the iron core is altered, as, for instance, by moving a magnet to and from it, currents will flow in the coil as long as the change continues.

While the magnetism of the core is *increasing*, the direction of the induced current will be such that it will tend to make the iron core a magnet having *opposite* polarity to that actually caused by the induction of the neighbouring magnet.

While the magnetism is *decreasing*, the direction of the induced current will be such that it will tend to make the iron core a magnet having the *same* polarity as that actually caused by the induction of the neighbouring magnet.

Moving Magnet.

The motion of a magnet past a coil will be fully discussed in the next chapter.

Construction of Electro-Magnets and Measurement of Magnetic Fields.

General Rule.

When we have a dynamo machine with magnets of a certain size, and wish to construct another with magnets of a different size, it is extremely important that we should be able to determine what difference in the strength of the field will be produced by the proposed change of size, or rather what change in size must be made to produce a desired change in the strength of field. It is impossible to calculate this *accurately* beforehand, but by the method I am about to describe the proper size of the magnets may be approximately calculated, and then the field produced may be accurately measured.

With magnets of the same general shape and proportions not magnetized to saturation, expending the same horse-power of magnetizing electricity in every pound weight or in every cubic inch of copper in the helix, the magnetic field produced is approximately proportional to the total weight of the magnets.

Saturation.

When a feeble current is sent round the coils of an electro-magnet, the magnetism is proportional to the current as the latter increases up to a certain point.

After a certain point the magnetism increases less rapidly than the current, the relative rate of increase becoming less and less, until at last a point is reached where further increase of current produces no increase of magnetism. When this point is reached the magnet is said to be *saturated.* In magnets intended for use in dynamo machines, the saturating point should not be approached. The maximum current that should be used is a current but little in excess of that for which the magnetism is nearly proportional to the current.

Measurement of Magnetic Field.

The following instrument (Plate XV.) has been designed by me for measuring the intensity of a magnetic field at

any point. It is a modification of one invented by the late M. Verdet.*

The principle on which the apparatus works is that, if a small coil of wire, placed in a magnetic field, moves rapidly for a quarter-turn round an axis at right angles to the axis of the coil, then the total quantity of electricity generated is simply proportional to the strength of the magnetic field at the coil.† When the motion is rapid, the quantity of electricity generated is proportional to the sine of half the angle through which the needle of a galvanometer connected to the moving coil will swing.

By using a reflecting galvanometer and diminishing its sensibility by shunts,‡ the angle of swing can be made very small, and then *the strength of the magnetic field will be simply proportional to the number of divisions of the scale passed over by the first swing of the light-spot.*

The practical form of the instrument is shown in Plate XV.

The little coil consists of an ebonite bobbin wound with fine wire, and is held in a light brass frame pivotted on an axis. Two stops limit its motion, so that it can turn through 90°. It is forced against one of the stops by means of a spring. By means of the handle it can be turned till it is forced against the other stop. On the handle being released, the bobbin turns instantly through 90°, under the action of the spring. The ends of the bobbin are connected to the poles of the galvanometer by means of two thin wires twisted together, so that accidental motions of the connecting wire through the magnetic field may not affect the galvanometer.

The stand of the instrument is so graduated that the exact position of the centre of the bobbin in the magnetic field can be noted, and so a map of the latter can be constructed with the intensity at each point.

* See "Œuvres de Verdet," tome i. notes et mémoires, p. 128; or my "Electricity," 2nd ed. vol. ii. p. 253.

† The current is of varying intensity and may be represented at each instant by $d\,C$, where C is the current in ampères. The total quantity Q of electricity generated in a time to where Q is measured in coulombs, and t is the time occupied by the bobbin in turning 90°, is

$$Q = \int \frac{d\,C}{d\,t}\,d\,t.$$

‡ The shunt used must not be varied during a set of experiments.

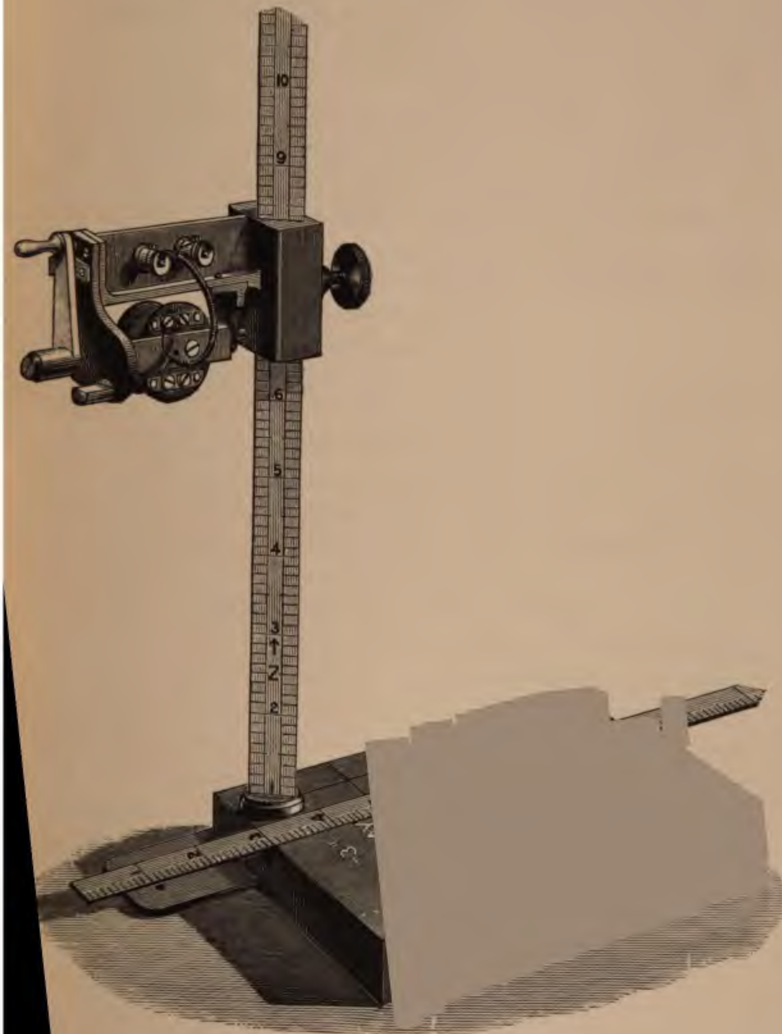


PLATE XV.—GORDON'S MAGNETIC FIELD MEASURER.

Lines are engraved on the base from which the horizontal distances in two directions (at right angles to each other) from the centre of the magnet can be measured by the rule shown lying on the base, and divisions in the vertical stem give the height above the face of the magnet. A gauge enables the bobbin to be set vertically over any point on the surface of the pole plate. With magnets such as are used in my alternating-current machines, the centre of the face of the pole plate is taken as "origin," distances measured along the circumference of the magnet-wheel are called x, those along the radius are called y, and those perpendicular to the face are called z.

Thus, such a memorandum as

$$x = 3'',\ y = 0,\ z = 4'',\ d = 270,\ C = 24 \text{ amps.},$$

would mean that at a point on the circumferential line 3 inches to one side of the centre of the magnet and 4 inches from its face, the magnetic field was such as to cause the light-spot to swing over 270 divisions of the scale when the magnetizing current was 24 ampères.

To determine when saturation commences, an ammeter is put in circuit with the magnet, and the current being increased 2 or 3 ampères at a time, the magnetic field due to each current is measured.

The ratio of magnetic field to current is then taken for each experiment, and when it begins to seriously diminish with increased current, we know we are approaching the saturation point of the magnet under examination.

For instance, let us suppose that with a particular magnet the following results are obtained: C as before representing the exciting current, d the strength of the field.

C	d	$\frac{d}{C}$
amps. 12	240	20
14	280	20
16	310	19·3
18	340	18·8
20	345	17·2
22	346	15·7

We see that after about 18 or 20 ampères we are not getting an increase of magnetism sufficient to pay the cost of the extra amount of current used, as we must remember that the H.P. expended in sending a current through the magnet-wire increases as the square of that current.

When used to compare the relative strengths of the fields produced by these magnets when the same horse-power of electricity is being expended per pound of copper, we proceed as follows :—

One magnet, which is our standard, is made precisely similar to one in some machine whose power is well known, the other is made of the proposed new form. Both are wound with wire of the same gauge and are connected in series, so that the same current goes through both. An ammeter in series with the magnets enables the current to be kept constant, and alternate observations are taken of the two fields.

To facilitate the rapid placing of the induction instrument in position, the pole plates may be advantageously let flush into wooden boards on which "latitude and longitude" lines are marked.

An iron core similar to the core of the proposed armature coil may be, if desired, fixed in position over the pole, and the disturbance of field produced by it can then be noted.

Apparatus for use in confined spaces.

When it is desired to measure the number of lines of force passing across any very narrow space, as, for instance, the number passing from a magnet pole to an armature core, the following modification of the instrument may be used. The coil may be wound in the form of a flat disc only one wire thick, and may be gummed between thin strips of card-board. This can be slid between the magnet pole and armature coil, and if jerked suddenly out, currents will be induced in it, whose total value is determined by the swing of the galvanometer needle exactly as described above.

COMPARATIVE MEASURES OF THE COEFFICIENTS OF MUTUAL INDUCTIONS OF VARIOUS SHAPED COILS AND ELECTRO-MAGNETS.

Let us suppose that we have a machine in which the magnets and coils have a certain shape, and that we wish to see whether some other shape is better or worse. The only way in which this can be determined accurately is by constructing a machine on the new plan, and trying it.

The following method* will, however, give results sufficiently accurate to be a very useful guide in devising the new machine, and involves only the comparatively trifling expense of making one magnet and one coil. The old and new coils are each placed in the field of their magnets. In

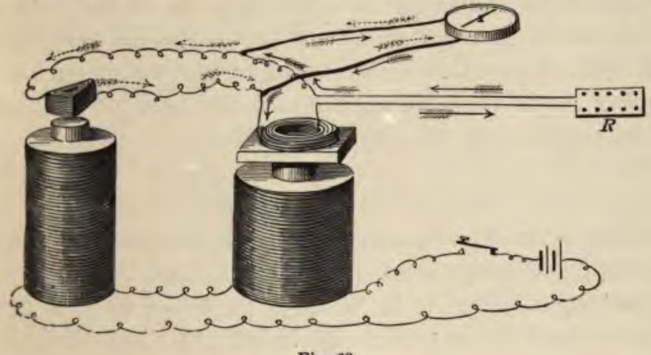


Fig. 62.

the case of the old coil this may be done without taking the machine to pieces. The electro-magnets are connected in series, so that the same battery or machine current can be sent through both. On this current being made and broken, transient currents will be induced in the two coils respectively. The coils are to be connected to each other "in quantity," and their joined ends to the two poles of a galvanometer, as in fig. 62, the connections being such that the currents sent through the galvanometer by the two coils respectively are in opposite directions.

On making and breaking contact, it will probably be found that the action of one of the coils is greater than that

* This paragraph is an attempt to explain in unmathematical language the method given in Maxwell's "Electricity," § 755, vol. ii. p. 364.

of the other, and consequently the needle is deflected. A resistance box R being introduced into the stronger circuit, the resistance is increased until the deflection is reduced to zero.

The currents being then equal, the E.M.F.s induced in the two portions of the circuit are directly proportional to the resistances; or if r_1 is the resistance of the left-hand coil, M_1 the coefficient of mutual induction between it and its magnet, and r_2, M_2 the corresponding quantities for the right-hand coil, we shall have,—

$$M_1 : M_2 :: r_1 : r_2 + R,$$

or,—

$$\frac{M_2}{M_1} = \frac{r_2 + R}{r_1}. \quad . \quad . \quad . \quad . \quad . \quad (45)$$

The relative inductions in different parts of the field can be of course determined by placing the coils in different symmetrical portions with regard to the magnets, i.e. by moving them both through equal fractions of the total distance traversed in a complete phase.

Self-Induction.

When a varying current, whether alternating or merely increasing and diminishing, is sent through a wire, it acts inductively on all wires in its neighbourhood, whether those wires belong to other circuits, *or are other convolutions of the same coil.*

When insulated wire is wound into a coil, and a varying current sent through it, each convolution acts inductively on all the other convolutions. This action is called *self-induction.*

While the current in a coil is increasing the mutual action of the wires delays the increase, because it causes an E.M.F. in the direction opposed to that generating the current.

While the current is decreasing, the mutual action of the wires delays the decrease, because it causes an E.M.F. in the same direction as that generating the current.

We see that one effect of the self-induction is to *retard the phase* of the current, i.e. to cause the alternations to take place a little later than they would otherwise have done. This retardation would not be noticed in any practical applications, so we need not concern ourselves with it.

The second effect of self-induction is to diminish the current.

It is found experimentally, and can be proved mathematically, that if a coil of wire forms part of a circuit, and an alternating E.M.F. sends a current through it, that the current will be much less than it would have been had the same resistance been interposed in the form of a straight wire.

Further, the proportional diminution becomes greater as the current is increased by the reduction of the resistance; and finally, for a given E.M.F., a given rate of alternation, and a coil of given shape, a limit is reached beyond which even reducing the resistance to zero does not increase the current.

For example: Suppose the coil to form one coil of a dynamo machine,* and let the rest of the circuit be incandescent lamps arranged in quantity, and let the resistance of the coil be very small compared to that even of a considerable number of lamps, then if there were no self-induction the current should proportion itself to the number of lamps inserted, as explained on page 26.

The effect of self-induction is, that, after a certain number of lamps are inserted, a limit is reached when diminishing the resistance by the insertion of more lamps does not proportionately increase the current; and that limit represents the number of those lamps which can be maintained on that circuit.

The mathematical proof of the above propositions is of a complex nature, but the geometrical diagram (fig. 63) is useful to illustrate the fact that self-induction diminishes the current.

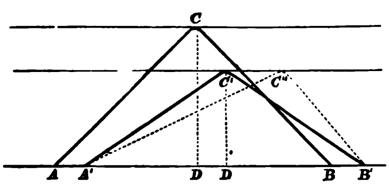


Fig. 63.

In fig. 63 let horizontal distance represent time, and let vertical height above the line A B′ represent strength of current. Let the points A and B represent the in-

* It must be remembered that *all* dynamo-machines produce alternating currents, though in some machines the currents are made direct after they leave the coils and before they leave the machine.

stants when a N. and a S. pole respectively pass the core of the coil.

Now, if there were no self-induction the rise and fall of the current would be represented by the curve A C B. The current would begin to increase from zero at the instant A as the N. pole passed the core, and would return to zero at the instant B as the S. pole passed. The height D C represents the maximum current; the steepness of the slope A C (i.e. the angle D A C) represents the rate of increase; that of the slope B C (i.e. the angle D B C) the rate of decrease.

Now one effect of self-induction is to retard the phase, i.e. to shift the zero points A B to the positions A′ B′. It does not, however, alter the length of the phase, and therefore the length A′ B′ remains equal to the length A B.

But both the rate of increase and the rate of decrease of the current are reduced by self-induction, and hence the slopes of the sides of the triangle are reduced, and are now represented by the sides A′ C′ and B′ C′.

But if there are two triangles on equal bases, the one with the smallest slope of sides must be the lowest, or must be contained between narrower parallels than the other; and we see that the height D′ C′ of the triangle A′ B′ C′ is less than that of the first triangle.

Now the total quantity of electricity which has passed during the phase, or the total integral value of the current, is represented by the total area of the curve; i.e. the area of the triangle A B C represents the total quantity of electricity which would have passed if there had been no self-induction, and the area of the triangle A′ B′ C′ represents the total quantity which has actually passed.

It is easy to see that the triangle A′ B′ C′ is the smaller of the two; for we know from Euclid that triangles on equal bases and between the same parallels are equal, and hence of two triangles on equal bases and between different parallels, the one between the narrowest parallels must be the smallest.

We have hitherto assumed that the retardations of both the increase and decrease are equal; but if they were not, but the curve had the form A′ C″ B′, the reasoning would

not be affected, for the triangles A′ C′ B′ and A′ C″ B′ are on the same base and between the same parallels, and hence are equal.

Coefficient of Self-induction.

The amount of self-induction which takes place with a given E.M.F., a given rate of alternation, and a given resistance, depends solely on the shape of the coil. For each coil there exists a quantity called the *coefficient of self-induction.* For a few simple forms of coils without iron cores, mathematicians are able to calculate this quantity. I am not aware, however, that they have succeeded in doing it for any of the oval, wedge-shaped, and ring-shaped coils most commonly used in machine construction, nor for any coils having iron cores such as are employed in nearly all the machines in use except the alternating Siemens. We can, however, obtain from the results of mathematical analysis certain information as to which form of coils are better and which worse than certain other forms, it being remembered that our object in settling the shape of our coils is to make the self-induction as small as possible consistently with the necessity of making the induction of the magnets as large as possible.

The circuit of minimum self-induction is a wire doubled back on itself, so that the two equal currents flowing in opposite directions are close together. This form cannot be used in machine construction, as opposed E.M.F.s would be induced in the two halves.

All resistance coils are wound in this way, i.e. the wire is doubled in the middle, the two ends are attached to the terminals, and the doubled wire wound on the reel. They have thus neither self-induction nor mutual-induction.

The next best form is a circuit consisting of a single thin wire. The thinness of the wire which can be used is in a machine limited by its resistance. When a single thick wire is used, the self-induction begins to increase, owing to the mutual action of the currents in different parts of the section on each other. In fact a thick wire acts like a bundle of thin ones.

With a coil of wire the self-induction is again increased. I do not know of any experiments or results of mathematical analysis which give us any information as to the best shape of coil which can be got into a magnetic field of a given strength, and whether it should be extended laterally or longitudinally, i.e. whether (the lines of force being for instance along the axis of the coil) the latter should be a rod or a disc.

Professor Clerk Maxwell has, however, calculated* the form which a coil without an iron core should have so as to have the *maximum coefficient of self-induction,* i.e. to be the worst possible coil for use in a machine. To obtain this result Professor Maxwell finds that—

If the transverse section of the coil is circular, the mean diameter of the coil should be 3.22 (fig. 64) times the diameter of the circular wire channel.

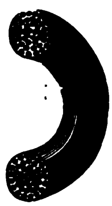


Fig. 64.

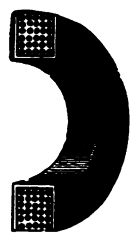


Fig. 65.

If the wire is wound in a square groove, i.e. if the groove has a square transverse section, the mean diameter of the coil should be 3.7 times the side of the wire channel. (Fig. 65.)

We see, therefore, that in constructing a machine we must make the shape of the coils differ as widely as possible from the above proportions.

When an iron core is used, the coefficient of self-induction is greatly increased. It must, however, be remembered that the mutual induction between the coil and the magnets is increased at the same time. Thus the introduction of an iron core increases the current by increasing the action be-

* Maxwell's "Electricity," § 706, vol. ii. p. 316.

tween coils and magnets, and decreases it by increasing the self-induction. Whether the net result is an increase or decrease of current, is a point on which there has been a great deal of controversy.

My own opinion is strongly in favour of iron cores, and I use them freely in my own machines, as do Edison, Crompton, and others; Messrs. Siemens Brothers, and Messrs. Ferranti make their machines without them.

In support of my own opinion, I may quote an experiment made on the Lachaussée-Lambotte machine during the Paris Exhibition of 1881. The Lachaussée-Lambotte machine is one with a number of separate coils. Two coils were constructed, one with an iron core and one without, all other conditions being exactly identical. It was found that the output of the coil with the iron core was "notably superior" to that of the other.*

COMPARISON OF THE COEFFICIENTS OF SELF-INDUCTION OF TWO COILS.

If we are doubtful which of two coils is the best to use in a machine, we may compare their coefficients of self-induction by means of the following rule which is given by Maxwell:—

Insert the two coils into two adjacent branches of a Wheatstone's bridge (fig. 66).

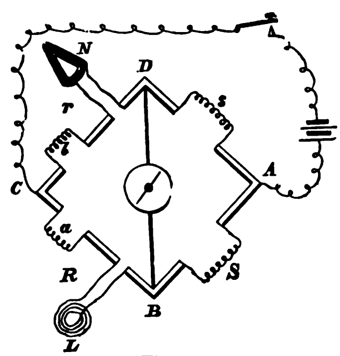


Fig. 66.

* Guerout, "La Lumière Electrique" (Journal), tom. iv., p. 389, Sept. 24, 1881.

Let the coefficients of self-induction of the two coils be L and N respectively. Let there be resistances a, b in the same sides of the bridge as the coils L and N respectively. Let the total resistance of the coil L, and the resistance a be R, and that of N and b be r.

Then in order that there shall be no permanent current through the galvanometer, we must have, as before, the products of opposite sides of the bridge equal, or,—

$$Sr = sR \quad . \quad . \quad . \quad . \quad . \quad . \quad (42)^*$$

The permanent current depends only on the resistances; the transient current, i.e. the sudden moving of the needle on making and breaking contact, depends on the ratio of the coefficients of self-induction of the two coils.

Professor Maxwell has shown † that the condition for no transient current is,—

$$\frac{L}{R} = \frac{N}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (46)$$

Now we cannot tell whether there is or is not a transient current, until we have arranged that there shall be no permanent current. We must therefore vary the resistances till there is no permanent current, and then see if there is a transient current. If there is, we must alter one of the resistances a, b, and at the same time alter the resistance s or S, till there is again no permanent current. We must then again try if there is a transient current. We must go on repeating the adjustments till there is no deflection of the needle, either permanent or transient, on making or breaking contact. When this is the case, equation (46) gives the ratio of the coefficients, or we may write it,—

$$\frac{L}{N} = \frac{R}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

Practical Method.

The above method is a troublesome one to use, and does

* Page 53.

† The condition of no galvanometer current is,—

$$\left(Rx + L\frac{dx}{dt}\right) sy = Sy\left(rx + N\frac{dx}{dt}\right)$$

where x and y are the currents in the two branches respectively.—Maxwell's "Electricity," § 757, vol. ii. p. 367.

not give its result in a very useful form. The following method may be used in practical work :—

To find how much a current of given E.M.F., and of a given rate of alternation, will be diminished by the self-induction of any coil.

Take the resistance of the coil in the ordinary way, then the amount of direct current which would pass through it with the given E.M.F. is given by the formula (1), p. 12,—

$$C_D = \frac{E}{R}$$

Then by means of an electro-dynamometer measure the amount C_A of alternating current which will pass with the same mean E.M.F. Then

$$P_{SI} = 100. \frac{C_D - C_A}{C_D} \quad . \quad . \quad . \quad (48)$$

is the percentage diminution of current caused by the self-induction, and

$$R_{SI} = \frac{C_D}{C_A} R \quad . \quad . \quad . \quad . \quad . \quad . \quad (49)$$

is the apparent resistance due to the true resistance R and to the self-induction acting together.

The apparent resistance is also given by the formula,—

$$R_{SI} = \frac{E}{C_A} \quad . \quad . \quad . \quad . \quad . \quad . \quad (50)*$$

These quantities P_{SI}, R_{SI}, will be different with different E.M.F.s and different numbers of alternations.

For a given E.M.F. and alternation rate, the ratio $\frac{C_D}{C_A}$ will be different with different values of $R + \rho$, where ρ is any other resistance that may be in series with R. In any given electrically lighted district, the E.M.F. and the alternation rate will be constant.

* Compare (3), page 12.

CHAPTER X.

General Principles of Electric Generators.

All electric generators may be considered as machines for moving magnets past coils of wire (which coils may or may not have iron cores) or coils of wire past magnets.

The motion is always circular, i.e. the coils are attached to the rim of a wheel, so that as the rim revolves, they pass the magnets again and again.

Efficiency of Machines.

In a well-constructed dynamo machine of any considerable size the amount of horse-power wasted in mechanical friction is extremely small. Almost the whole horse-power expended is used in producing electric currents, which in their turn produce heat.

Part of the heat is produced in the lamps, part in the conducting wires, and part in the coils of the machine itself. The heat produced in the lamps is useful, that produced in the machine and wires is useless and injurious.

The efficiency of a machine is the ratio of the useful to the total heat produced, that is, of the useful to the sum of the useful and useless heat.

Our object in constructing a machine is to make this ratio as high as possible, or in other words, to make the quantity of heat produced in the machine and leading wires as low as possible. Now the relative amounts of heat produced in different parts of a circuit all traversed by the same current are simply proportional to the relative resistances of the different parts.

We can diminish the heating of the leading wires by

making them thicker, the limit being reached when the annual interest on the cost of the wires becomes a more serious item of expense than the annual cost of the heat wasted.

We must diminish the resistance of the wire of the machine as much as possible, without unduly diminishing the E.M.F. We must remember that the E.M.F. depends among other things on the length of wire on the coil, for the longer the wire the more lines of force it will cut.

If we make our wire long and thin we shall increase our resistance; if we make it long and thick, a considerable part of it will be a long way from the poles of the magnets.

We must remember, however, that increasing the length of wire is not the only way to increase the E.M.F., for the E.M.F. is also increased by increasing the strength of the magnetic field, and by increasing the velocity with which the wires move through it, or with which it moves over the wires.

The magnets may be made very strong. The limit of their power is, if steel magnets are used, given by the fact that the size of a steel magnet increases with its power, and if it is very large its pole cannot all get near the wire.

With electro-magnets the size is limited by the expense of the current required to excite them.

The third way of increasing the E.M.F. is by increasing the speed of the machine. The *possible* speed at which a machine may be run is limited only by the centrifugal force tending to make it fly to pieces. The *practical* speed is limited by mechanical and engineering considerations to a much lower limit than would be allowed by the centrifugal force, for high speed means increased wear and tear of machinery and greater liability to break down, and it is very bad policy to diminish the cost of a machine per lamp say twenty per cent., by an increase of speed which will double or treble the depreciation rate.

General Types.

An immense number of generators have been devised, of

different forms, but they may all be resolved into two general types, viz.:—

(1) The "alternating" type, where a number of coils are placed on the rim of one wheel, and a number of magnets on the rim of another concentric with it, and one of the wheels being fixed, the other is caused to revolve. "Alternating currents," i.e. currents alternately in opposite directions, are produced in the coils, and are either used as alternating currents, or are converted into direct currents by being passed through a "commutator" before they go into the line.

(2) The "direct" type, where the wire is wound continuously round a ring of iron, the winding being as if the wire were wound spirally round a long iron bar, which was afterwards bent so as to form a ring. In this type the ring revolves between two (or sometimes four or six) magnet-poles, and although the currents are alternately in opposite directions in any portion of the wire, they are always in the same direction in the wires which are passing either pole. These currents are "collected" by suitable apparatus and are passed as "direct currents" into the line.

We shall first discuss the *alternating* type, as it is the simpler of the two, and we will consider the—

Motion of a Magnet Pole past a Coil with an Iron Core.

If the circuit is broken so that no current can be induced, *no work* * is done as the magnet passes the core, for it induces a polarity opposite to its own, causing an attraction; and as it approaches the core, the attraction helps the motion; and as it leaves it, it retards the motion; and these two *opposite* actions are *equal*.

We note that while the magnet is *approaching* the core the magnetism of the latter is *increasing*, while it leaves it is decreasing.

* No work is done by an E.M.F. when the current cannot flow. Compare equation 10, page 16 :—

$$\text{H.P.} = \frac{E^2}{746R} \quad \text{When R is infinite, H.P. is zero.}$$

When the circuit of the coil surrounding the core is closed, currents flow such that, while the magnet is approaching and the magnetism of the core increasing, they tend to cause a polarity opposite to the induced polarity of the core, and the same as the polarity of the approaching magnet, and hence *diminish* the attraction which is *helping* the motion.

When the magnet has passed the core, and the magnetism of the latter is decreasing, the induced currents tend to cause a polarity the same as that induced by the magnet, and hence *increase* the attraction which is *retarding* the motion of the magnet.

Work has then to be expended in moving the magnet, and this work is proportional to the sum of the two differences of attraction mentioned, namely, to the sum of the diminution of attraction when the poles were approaching, and of the increase of attraction when they were receding. This work is the work expended in producing the currents.

The above argument may be more concisely expressed by means of symbols.* Let W be the total work required to move the magnet from the iron core to a distant point when no current is allowed to flow. Then $-W$ will be the work required to move it from a distant point to the core. The total work required to move it past the core, i.e. from a distant point on one side to a distant point on the other, will be the sum of these two quantities, i.e. will be $W - W = 0$.

When the circuit is closed the induced currents diminish the negative work done to bring the approaching poles together, by a quantity which we will call D, and it becomes $-(W - D)$. When the poles are receding, the induced currents increase the work required to separate them by the same amount, and it becomes $W + D$.

The total amount of work done in passing the pole is then

$$W + D - (W - D) = 2D. \quad . \quad . \quad (51)$$

* The student who is unfamiliar with algebra is advised not to trouble himself with this paragraph, as it is only a different way of stating what has already been stated in words.

Phases of an Alternate-current Machine. (Plate XVI.)

Plate XVI. represents the phases of a typical alternate-current machine during one complete cycle of change, i.e. from the time a S. pole leaves a given core to the time a S. pole arrives at it again.

The three circles A, B, C, which in practice would be arranged with others round a large ring, represent three coils of the machine. The small central circles are their iron cores. The squares are the poles of the moving magnets. The five lines represent the same three coils at five successive phases of the cycle.

We will fix our attention on the changes which take place in the centre coil B.

In position 1, the core of B has a S. pole exactly over it, and has the maximum of induced N. magnetism. When the magnets begin to move towards position 2, the N. polarity of the core of B diminishes, as a S. pole is leaving it and a N. pole approaching it. A current is therefore generated in the direction *opposite* to that which would make a *N. pole* in B, i.e. in the direction of the arrows in line 2.

In position 2 the core has no polarity, for it is acted on equally by a N. and by a S. pole. The instant the magnets have passed position 2 the core begins to acquire a S. polarity, as the action of the receding S. pole is diminishing and that of the approaching N. pole increasing.

The increasing S. polarity induces a current in B in the *same* direction as would make a *S. pole* in B, i.e. in the same direction as before. Thus the current from position 1 to position 3 is in the same direction.

In position 3 the S. magnetism has attained its maximum, and now begins to diminish, hence a current begins to flow in the opposite direction, i.e. the direction shown by the arrows in position 4, and it continues to flow in that direction till position 5 is reached, when it is again reversed.

Thus we see that the direction of the current reverses at positions 1, 3, 5, and therefore, by the law of continuity, it must have zero value in those positions.

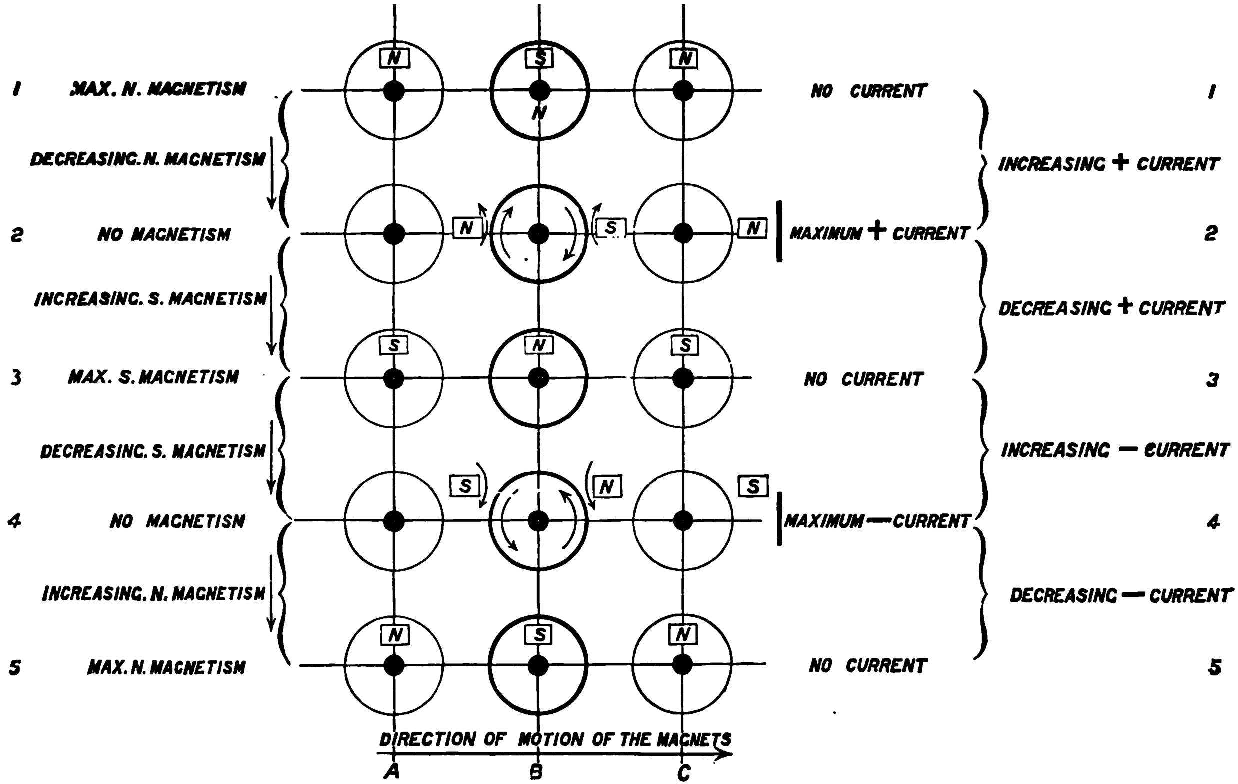


PLATE XVI.—PHASES OF AN ALTERNATE CURRENT MACHINE.

It attains its maximum value in what we will call the + direction at some position between positions 1 and 3, and its maximum value in the − direction, in some position between 3 and 5.

These maxima will be, approximately, in positions 2 and 4, but will not in general be accurately in those positions.

The positions of the maxima are displaced by the fact that the phase of an induced soft-iron magnet lags a little behind the phase of the inducing magnet, and owing to iron requiring a certain small time to acquire its induced state. The phase of an increasing induced magnet will lag a little more than that of a decreasing one, as iron gains magnetism less quickly than it loses it. The displacements depend on the size and hardness of the iron cores and on the speed of the moving magnets.

The minima positions 1, 3, 5 will also be displaced, but probably not so much as the maxima.

The maxima are also displaced by self-induction, as explained on page 122.

If we consider the direct actions of the magnet-poles on the wire, we see that in the maxima positions 2 and 4 the poles are acting on both sides of the coil.

Reaction on the Magnets.

We now have to consider whether the induced currents have any reaction on the magnets, and if so, whether it tends to strengthen or to weaken them.

We know that any iron placed near a magnet-pole increases its strength. The poles therefore have their maximum strengths in positions 1, 3, 5, and their minimum strengths in positions 2, 4. When no induced currents are flowing, the strength of the poles decreases in moving from 1 to 2 and from 3 to 4, and increases again in moving from 2 to 3 and from 4 to 5.

Let us now close the circuits and consider the actions of the induced currents on the magnets.

It will be simpler if we suppose the magnets to be

electro-magnets, and consider the action of the induced currents on the magnetizing currents. The small arrows surrounding the square magnets show the directions of the magnetizing currents producing the polarities marked on them.

We remember that an increasing current induces another in the opposite direction to itself, and a decreasing current one in the same direction.

We assume the electro-magnets to be all connected together and magnetized by the same current, so that any change caused by an action on the current in any one of them is equally divided between all, so that they remain equal to each other.

Now from position 1 to position 2 there is an increasing current in the coil B, and hence it induces currents opposite to itself in the coils of the electro-magnets. Hence we see, by referring to Plate XVI., line 2, that the reaction diminishes the magnetism of the N. pole, and increases that of the S. pole.

But through the whole of the motion from position 1 to position 2 the S. pole *is nearer to the core* than the N. pole; hence the increase of the magnetizing current caused by the reaction of the induced current on the S. electro-magnet pole is a little greater than the decrease caused by the reaction on the N. electro-magnet pole, and hence the total effect of the induced current between positions 1 and 2 is to cause a slight *increase* of the power of the magnets.

From position 2 to position 3 there is a decreasing current in coil B, and hence it induces a current in neighbouring coils in the same direction as itself. Its tendency is thus to decrease the S. pole and to increase the N. pole. But during this portion of the motion the S. pole is further away from the coil than the N. pole, and hence the decrease of the S. pole is less than the increase of the N. pole, and there is in this phase also a small total *increase* of magnetism caused by the reaction of the coil.

In the same way an increase occurs in phases 3 to 4, and 4 to 5.

Effect of Self-Induction.

Whenever, as in dynamo machines, the currents in coils are rapidly reversed, the effects of self-induction become important.

Speaking generally, the effect of self-induction is that, with a given speed, magnet, and armature coil, the current produced is less than it would otherwise be.

This diminution, however, does not, to the best of my belief, waste energy or diminish the *efficiency* of the machine; it only diminishes its output.

With the diminution of output comes a corresponding diminution of H.P., so that if by running the machine faster we bring the output up to what it would have been if there had been no self-induction, we only increase the H.P. in the same proportion, so that the ratio of output to H.P., i.e. the efficiency of the machine, remains unaltered.

Thus self-induction increases the size of machine required to feed a certain number of lamps, but it does not perceptibly increase the H.P. required to drive the machine with that number of lamps on it.

The effect of self-induction increases as the current increases, and therefore *short circuiting a coil of an alternating machine does not indefinitely increase the current in that coil, and seldom increases it enough to injure the insulation.*

The effect of self-induction in diminishing output can be utilized in regulating machines; for if a number of coils be connected in quantity to a number of lamps in quantity, then cutting out one or more coils reduces the number of coils through which the current can flow, and thus increases the self-induction and diminishes the E.M.F. at the lamps.

General Principle of Direct Current Machines.

The direct current type of machine may be divided into two sub-types, namely, the "Gramme" machine and the "Siemens" machine.

THE GRAMME SUB-TYPE.

Fig. 67 is a diagram of a machine of the first sub-type. It consists, as we have already stated, of a ring of soft iron round which wire is wound as a continuous spiral, forming a closed circuit.

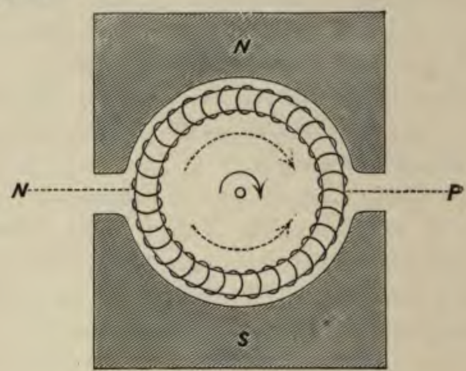


Fig. 67.

It revolves between two poles of opposite names, the lines of force from which terminate in the ring, as shown in fig. 68, which represents a section made through fig. 67 by a plane in the line N S of fig. 67, and at right angles to the plane of the paper.

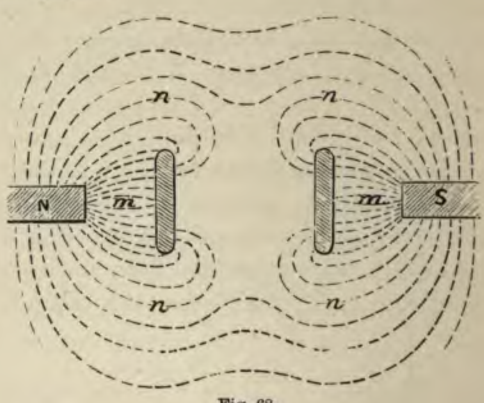


Fig. 68.

As the ring revolves these lines of force are cut by the moving wires, and electro-motive forces are generated in the two halves of the ring *in opposite directions,* so that they

meet and oppose one another at the neutral points N P, as in fig. 69.

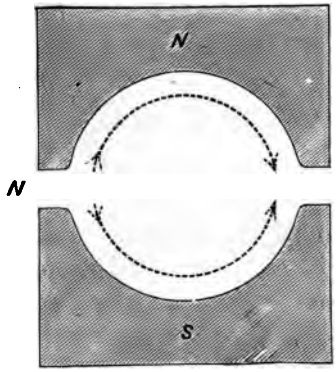


Fig. 69.

As long as no further connections are made, no current is generated, and no H.P. expended. If, however, the points N P are connected through an external circuit, such as a

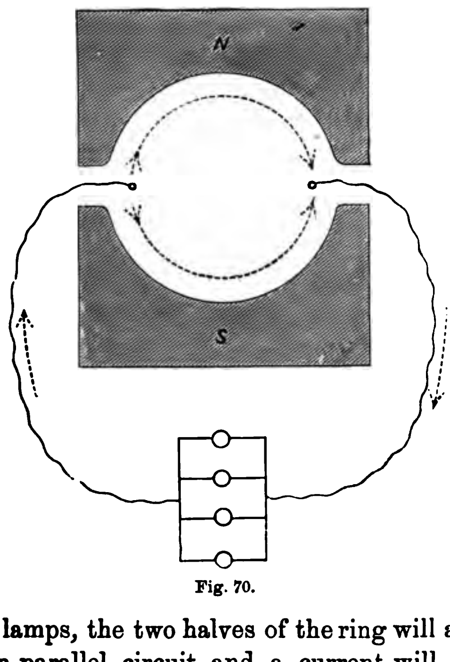


Fig. 70.

number of lamps, the two halves of the ring will act like two batteries in parallel circuit, and a current will flow, as in fig. 70.

We see that, owing to the ring being in motion and the neutral point necessarily at rest, a permanent connection between the line and the wire in the ring cannot be made, but a special device has to be employed.

The Collector.

The collector is made of a barrel of wood or other insulating material, shown in the centre of fig. 71, on which are a number of insulated metal strips. Each of these strips is connected by a wire to the part of the spiral wire opposite to it. Two metal brushes press or rub onthe strips at the points * P N, where the opposite electro-motive forces diverge and join again. These brushes convey the current to the external circuit.

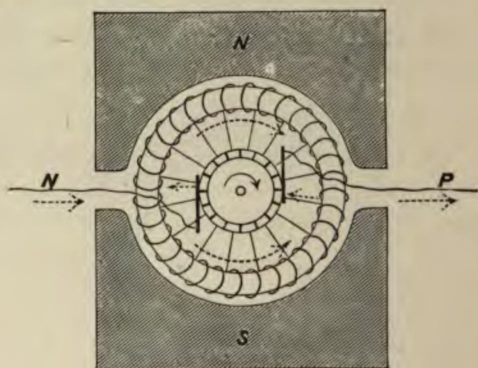


Fig. 71.

The Siemens Sub-Type.

In this type of machine the wire is wound longitudinally round an iron barrel. It differs from the Gramme ring by the omission of those parts of the wire which pass inside the ring. Fig. 72 shows the Gramme type in section, fig. 74 the Siemens type, and fig. 73 an imaginary intermediate type.

* These points are not usually the symmetrical points, as shown in fig. 71, but are displaced by the time required for the iron of the ring to change its magnetism, as will be explained later.

The collector in this type of machine is similar to that in the Gramme type.

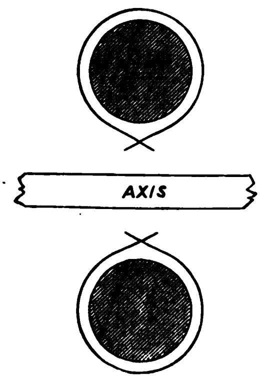


Fig. 72.

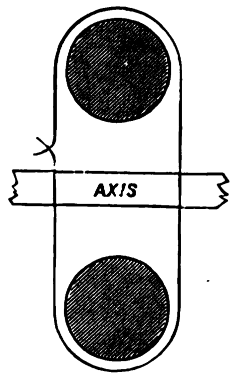


Fig. 73.

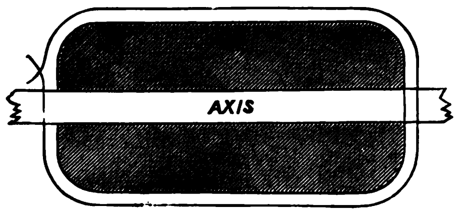


Fig. 74.

PRODUCTION OF MAGNETISM IN THE FIELD MAGNETS.

The direct type of machine can "excite" its own magnets, as a portion of the current generated is sent round their coils. The alternating type has to have its magnets excited by a small auxiliary direct-current machine. There are three forms in which the direct-current machines are constructed to excite their own magnets, and they are called respectively, "Series-wound," "Shunt-wound," and "Compound."

In the *series-wound* dynamos the magnets are wound with a comparatively short length of wire thick enough to carry the whole current generated, and are connected *in series* with the armature and brushes. The first time such a machine is worked it must be excited separately by a battery or by another machine.

When once the magnets have been excited, a feeble

residual magnetism will remain in them. On the machine being worked this feeble magnetism developes a feeble current in the armature ring. This feeble current passing through the magnets strengthens them, and they in turn strengthen the current in the armature. These alternate reactions go on until the maximum current that the machine can give is being generated.*

This maximum is limited first by the external resistance, or, if the machine be short-circuited, it is limited by the magnets approaching their saturation-point, and by the internal resistance of the armature.

The *practical* current that can be taken out of such a machine is limited by the capacity of the wire to carry it without undue heating.

Short-circuiting a series-wound dynamo will do either one of three things: burn through the insulator, or by the extra H.P. absorbed, throw off the belt or pull up the steam-engine.

In *shunt-wound* dynamos the magnets are wound with a large quantity of thin wire, which is connected to the armature brushes *in quantity* with the lamps or other external circuit. The currents in the magnets and lamps then divide according to the ordinary rules of divided circuits. The same alternate re-inforcement of the current and magnets goes on as in the series machines. Short-circuiting a shunt-wound dynamo simply stops the current, as it removes all the current from the magnets.

In *compound* machines the magnets are wound partly shunt and partly series. These machines will be discussed in the chapter on the regulation of dynamos.

* The time required for the current to reach its maximum varies from one or two seconds with small machines to about three minutes in the large Edison machine.

CHAPTER XI.

ON DESIGNING DYNAMOS AND ON THEIR MECHANICAL CONSTRUCTION.

Application of Mathematical Analysis to Machine Construction.

Engineers are often disappointed to find the small amount of help which mathematicians are able to give them in practical work. For instance, if we give to a mathematician scale-drawings of two forms of coils, he is seldom able to tell us what will be their relative co-efficients of self-induction.

The failure of mathematical analysis to help us in the more complex problems of our profession has too often caused engineers to neglect not only mathematical analysis, but even arithmetical calculation, and consequently working empirically, to make numerous costly and even dangerous mistakes. Without mathematical reasoning (although it need not necessarily be expressed in symbolical language) no real progress can be made. The best work will, however, be done by men who, possessing mathematical knowledge, will yet not blindly trust to their symbols, but will insist on knowing the physical and material meaning, not only of the two ends of their analysis, but of every intermediate step.

Mathematical reasoning is an invaluable aid to the engineer, but whenever he trusts to mathematical analysis

instead of to engineering skill, whenever he prefers the manipulation of symbols to the manipulation of machinery, disastrous failure will be the result.

The reason of the untrustworthiness of mathematical results is due not so much to any defect in the mathematics as to the impatience with which the purely mathematical temperament regards the experimental limitations which are necessarily present in practical work, but which the mathematician is not accustomed to in his own studies, and to the complexity of the conditions of the problems presented to him.

The mathematician working on paper is at liberty to assume conditions which cannot be satisfied in practice; for instance, that all parts of a coil of wire are equidistant from the magnet, and that parts of the machine not intended to act on each other are at an infinite distance apart.

Further, the mathematician generally considers his result complete if he produces a formula connecting the quantity whose value is required with four or five "constants," whose value he assumes to be known when he has indicated them by the earlier letters of the alphabet. As a rule, the measurement of these constants is a matter of greater experimental difficulty and expense than the direct determination of the quantity required.

Lastly, mathematicians are seldom engineers, and it consequently sometimes happens that a machine which is excellent electrically, is so designed that it could neither be constructed, put together, nor taken to pieces.* Perhaps it has all its bolts in positions which cannot be reached by the spanner, or has its revolving part supported only at one end, so that it must shake and rattle directly it is set in motion.

Therefore, as mathematical knowledge is essential, and as mathematicians cannot be trusted to design machines, the only way in which real progress can be insured, is for practical engineers to acquire for themselves such mathematical knowledge as they require. Then their mathematics

* An interesting description of such a machine, the invention of an eminent mathematician, has been recently published in the *Patent Journal*.

will again and again assist them in their designs, and their practical experience will tell them when symbolic reasoning has led them to an absurd result.

In designing a dynamo, a first sketch may be made showing the magnets and armature coils in their proposed relative positions. The proportioning of the relative sizes of magnets and armature coils in any new type of machine is more an art than a science, i.e. it depends more on the individual skill of the designer than on rules which can be printed.

It is a good plan in designing new types to draw everything full size "freehand" on a large board, and then, when satisfied with the appearance, to measure the sketch, varying it as we go on, to correct disproportions, and to bring the dimensions to even measurement. Scale-drawings can then be made from the sketch, and will be ready for criticisms based on measurements of the quantities of iron and copper in the magnets and armature as drawn; for it is much easier to calculate what a machine of certain proportions will do, and to alter those proportions to make it do something else, than to design a machine directly for a particular work.

When once a machine of any particular type has been successfully tried, it is easy to design another of the same type, but of different size. If we are designing a machine larger than our model, it is safe practice to consider that the strength of magnetic field, the proportions of the magnets being unaltered, is proportional to their weight, and that the proportion of armature to magnets should remain unaltered. If we are making a machine smaller than our model, the magnets must be somewhat larger than this rule would give. If the electro-motive force of the big machine is to be the same as that of the small one, the wire in the armature must be proportionately shorter and thicker.

The simplest way of working is to calculate what would be the E.M.F. if the wire had been the same as on the model, and then to calculate the proper gauge of wire by the following rules:—

(1) *With an armature coil carrying a given volume of wire,*

then other things being equal, the E.M.F. is proportional to the length of the wire.

(2) *The volume of wire on an armature coil is proportional to the length of the wire multiplied by its section.*

Whence--

With a given armature coil the E.M.F. will be inversely proportional to the section of the wire.

Example.

The wire on an armature coil is ·105 inch diameter, and the E.M.F. is 170 volts. What must be the diameter to give an E.M.F. of 100 volts? From the tables at the end of this book we see that the section of wire ·105 inch diameter is ·00882 sq. inch.

The section of the desired wire must be then—

$$\frac{170}{100} \times \cdot 00882 = \cdot 0149,$$

and a further reference to the tables shows that this is a wire whose diameter is ·138 inch.

In designing a machine larger than a model, but of similar proportions, the output is a function of the linear dimensions, say of the diameter of the revolving wheel, and mathematical analysis shows that the output should increase in a ratio between the 4th and 5th power of the ratio of diameters, say the $4\frac{1}{2}$th power.

This means that if a machine of a certain diameter could feed a certain number of lamps, one of twice the diameter could feed $2^{4\frac{1}{2}}$ or 22·6 times that number.

In practice, however, the result obtained does not much exceed the *third power* or cube of the diameter, which means that if a machine of a certain diameter feeds a certain number of lamps, one of twice the diameter will feed 2^3 or 8 times that number. In other words, the practical rule is that the output will be proportional to the *weight* of the machine.

The use of the 3rd power in calculations is very safe practice and allows ample margin, and the engineer who uses it as the basis of his work is not likely to be disappointed, but will always find that his machines will do rather more than he has promised they shall do.

We may here note that an approximate rule for the quantity of wire a bobbin will hold is that for moderately thick wire, double cotton covered, each cubic inch of space will hold $\frac{1}{6}$lb. of wire.

Example.

How much No. 7 wire would a circular bobbin hold, whose external diameter is 8 inches, internal (i.e. outside the tube), $3\frac{1}{2}$ inches, length between flanges 5 inches?

Area of circle 5 in. in diam. is	19·6 sq. in.		See tables at end of book.
$3\frac{1}{2}$ „ „	9·6 „		
Difference	10·0 „	= area of wire space.	

Whence volume of wire space $= 5 \times 10 = 50$ cubic inches, and the weight of wire will be $\frac{50}{6} = 8\frac{1}{3}$ lbs.

This rule is, of course, a rough one, but it is near enough to be very useful in practice, and is quite near enough to purchase wire by.

The next stage of the design should be the making of a specimen magnet of the proposed pattern and size, and the examination of its field with the Field-measurer already described.*

Varying currents should be used up to the full H.P. which it is proposed to expend in the magnet, and the field should be measured for each current.

If the magnet approaches saturation before the current has received its maximum value, it means that there is not enough iron in the magnet in proportion to the copper and to the H.P., and the core must be made larger.

If the machine is one of a type which has already been tried, then a magnet of the model machine may be placed in series with that of the proposed machine, and the same current sent through the two, and their fields can be compared.

For this experiment the bobbins of the two magnets must be wound with wire of the same gauge, and then the H.P.s expended per cubic inch will be the same in both. When

* See page 117, Plate XV.

the machine is constructed, any other gauge of wire may be used that suits the E.M.F. of the exciting current. This change will not alter the strength of field produced per H.P. expended in the magnetizing coil.

Armature Coils.

Armature coils (i.e. the coils in which the current is to be induced) are made both with or without iron cores, and there has been much controversy as to which gives the better result.

The use of iron increases on the one hand the useful induction, and on the other it increases the useless self-induction, and wastes a certain quantity of heat in the reversals of its magnetism, and in the currents induced in itself. The two last causes of waste can be greatly reduced by proper annealing and by suitable slits in the metals.

My own experience is strongly in favour of the use of iron cores, for both electrical and mechanical reasons.

I approve of them electrically because I believe that the increase of useful effect is very much greater than the increase of waste effect, and because of the much greater length of armature coil (measured along the axis) which can be brought into the magnetic field when the lines of that field are concentrated by an iron core, than when they are diffused. My own and the De Meritens alternating machines, and nearly all direct-current machines, are made with iron cores, and the alternating machines of Siemens and Ferranti are made without them.

The mechanical advantages of iron cores are also very great, as they allow machines to be strongly constructed, which is not possible when the cores or other supports of the coils are made of wood.

As to the proportions of armatures, no mathematical rule can be laid down, but a skilled engineer can generally sketch out an armature to work under any given circumstances, which will, when tried, be found to be successful, and such that any deviation from it will be less successful.

In making a machine of a known type, the length of wire required to give the same E.M.F. as the model is by theory inversely proportional to the product of the number

of reversals per minute by the strength of the magnetic field (so that, for instance, if the magnetic field were twice as strong, and the number of reversals the same as in the model, the wire in the armature should be half the length that it has in the model).

In practice this rule is not quite accurate, but has to be modified by practical considerations. The section of the wire is that which, with the calculated length, will just fill the armature bobbin.

This rule (as modified) will give a result near enough to the correct one to enable us to wind one bobbin for experiment. Having tried it in the machine and measured the E.M.F. produced, we can calculate the diameter of the wire, which will give us the exact E.M.F. wanted, by the rule given on page 146.

Having drawn the magnets and coils of right proportions and in their right positions, we have to think how they are to be supported in those positions, and how one or other of them can be moved rapidly past the other, and here we meet our first difficulty.

If metal passes through a magnetic field, electro-motive forces are induced in it. If the metal forms a closed circuit, these electro-motive forces will produce currents which heat the metal and consume horse-power.

If the metal forms a circuit of very low resistance, the heating and horse-power will both be very great. If, for instance, a metal disc be turned between the poles of a powerful magnet, it will take an enormous horse-power to turn it rapidly, and the heat will very likely be sufficient to melt the disc.

In carrying coils of wire through a magnetic field, rigidity and strength are required in the supports connecting the moving coils to the driving shaft; rigidity, because it is necessary that the rapidly moving coils should pass very close to the magnet faces, and strength to resist the horse-power pull and the centrifugal force.

The problem before us then is to support the moving coils or magnets in such a way that there shall be ample strength, and yet that currents should not be induced in the supports of the armature coils.

As far as these conditions are concerned, there is a great advantage in making the magnets move and keeping the coils fixed, as metal may be freely used to carry the moving magnets, while the armature coils, being only strained by the horse-power pull, and not by centrifugal force, need not be nearly so strongly supported as if subjected to the latter, and the supports, if of metal, can be slit to check the circulation of currents. This plan also enables the supports and cores to be made hollow and to have water run through them, thus increasing the output that the machine can be made to give without undue heating.

It must be remembered that the horse-power pull and the centrifugal force do not add together, as they act at right angles to each other, the former acting along a tangent to the revolving-wheel, and the latter along its radius.

Calculation of Centrifugal Force.

The centrifugal force F in pounds exercised by any body attached to the rim of a revolving-wheel, is given by the formula

$$F = \cdot 00034\, WRN^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad (52)$$

where W is the weight in pounds,* R the radius in feet, and N the number of revolutions per minute.

Example.

What is the centrifugal force exercised by a magnet weighing 180 lbs., attached to the rim of a wheel 2 feet in diameter, revolving at the rate of 750 revolutions per minute?

We have from (52)—

$$F = \cdot 00034 \times 180 \times 1 \times 750^2 = 34{,}400 \text{ lbs.} = 15\cdot 3 \text{ tons.}$$

The total strain tending to pull a wheel into two halves is the total centrifugal force, taking into account all the weight of the rim, and of any weights attached to it, divided by π the ratio of the circumference of a circle to its diameter; † or we may write it—

$$f = \frac{F}{\pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (53)$$

* If W be taken as the weight in tons, F will be the force in tons.

† $\pi = 3\cdot 1416$.

In calculating the strength of the wheel, we may allow double the section of the rim at any point, as it is held at two points, one at each end of a diameter.

Example.

What is the force tending to split a fly-wheel into two halves when the diameter is 6 feet, weight of rim one ton, and speed 100 revolutions per minute?

We have

$$f = \frac{\cdot 00034 \times 3 \times 2240 \times 100^2}{3 \cdot 1416} = 7300 \text{ lbs.} = 3\tfrac{1}{4} \text{ tons.}$$

A rim of this weight and diameter would have a cross section of about 38 square inches, but the cross section available for resisting the strain would be double this, or 76 square inches.

Horse-Power Pull.

When we know the horse-power, the speed, and the diameter of the wheel, we can calculate the tangential strain as follows:—

Let us suppose that, instead of carrying coils round and generating electricity, a wheel, of the diameter which the wheel of the dynamo has at the centre of the coils, is expending the same horse-power, by winding a string round its rim and raising a weight, then this weight will be equal to the tangential strain.

Let V be the velocity of the rim in feet per minute, then

$$V = \pi D N \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (54)$$

where D is the diameter in feet, and N the number of revolutions per minute.

We know that a horse-power equals 33,000 foot-pounds per minute, and the number of pounds which one horse-power will raise in a minute is therefore 33,000 divided by the height in feet to which the weight is raised.

The weight W in pounds which a horse-power can raise at a speed V (where V would be the rate at which the string would be wound round the wheel) is then

$$W = \frac{33,000}{V} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (55)$$

or substituting the value of V from (54), we get

$$W = \frac{33{,}000}{\pi DN} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (56)$$

and the weight which any number H.P. of horse-power could raise under the same circumstances would be

$$W = \frac{\text{H.P.} \times 33{,}000}{V} = \frac{\text{H.P.} \times 33{,}000}{\pi DN} \quad . \quad . \quad (57)$$

and this weight is the total tangential strain at the rim of the wheel.

Having got the total tangential strain, then dividing the result by the number of coils in the rim, gives us the strain on each coil.

Example.

In a dynamo having 128 armature coils, a wheel 8 feet in diameter is revolving 180 times a minute, and absorbing 500 H.P., what is the tangential strain in each armature coil?

The total tangential strain is from (57)—

$$W = \frac{500 \times 33{,}000}{3{\cdot}14 \times 8 \times 180} = 3640 \text{ lbs.},$$

and the strain on each coil is

$$\frac{W}{128} = 28{\cdot}4 \text{ lbs.}$$

Factor of Safety.

The *factor of safety* in any work is the ratio of the calculated breaking strain to the actual strain which the work is subjected to. For instance, if a rod which would break with a weight of 15 tons, supported a weight of 3 tons, its factor of safety under that load would be $\frac{15}{3} = 5$.

In dynamo work the strains are so sudden and the strengths are so altered by unequal heating, that the factor of safety should be very large; never less than 15 in the moving parts, and 10 in the parts which are at rest. Indeed in my own practice I never use less than 20 in the moving parts.

Strength of Materials.

The strengths of various materials per square inch section are given in the appendix to this book.

Use of the Factor of Safety in Designing.

We wish to know how many square inches of metal are required for safety under given conditions of strain.

Let F be the straining force (centrifugal or otherwise) in tons, ϕ the factor of safety, and B the breaking strain of the material in tons per square inch, then A the required area or section will be

$$A = \frac{\phi F}{B} \qquad (58)$$

Example.

Let us suppose we have a wrought-iron disc, 3 inches thick and 2 feet diameter at magnet centres, and that we are fixing magnets round its rim by passing their cores through holes drilled in the 2 foot circle. Speed to be 750 revolutions per minute. Weight of each magnet, 180 lbs. What should be the radius of metal outside the holes to give a factor of safety of 20?

By the example given on page 150, with the same data, the centrifugal force will be $F = 15{\cdot}3$ tons, we have $\phi = 20$, and we may take B at 25 tons per square inch.

Thus, by (58) the area must be

$$A = \frac{15{\cdot}3 \times 20}{25} = 12{\cdot}3 \text{ square inches.}$$

But, in order for the magnet to tear out, it must shear two faces, for it must cut out a piece from the rim as wide as itself. Hence the area of each face will be 6·15 square inches. The thickness being 3 inches, this would give the necessary metal outside the magnet-hole at, say $2\frac{1}{8}$ inches, measured along the radius.

Speed.

The faster the dynamo runs the greater will be its output, and the output will be nearly proportional to the speed. It therefore appears at first sight that dynamos should be run

as fast as possible. It is usually noticed that when electricians who are not skilled engineers commence to design dynamos they make them to run at immense speeds, and consequently fail to produce useful machines. Most of the breakdowns which have caused the public to distrust electric light have been due to dynamos being run at too high a speed. When first I commenced to design dynamos, I fell into the common error of supposing that great speeds were advantageous, and in an article on "Electric Lighting," which I communicated to the *Quarterly Review* for October, 1881, I supported this view, and it was not until I had had one of my high-speed machines fly to pieces, with the result of wrecking the portion of the factory in which it stood, and destroying the result of nine months' labour, that I modified my views.

It must be remembered that the annual cost of a dynamo is not its first cost, but is the interest and depreciation on that first cost, and that the depreciation rate per cent. is much greater at high speeds than at low ones. By increasing the speed we diminish the first cost per lamp, but we may so much increase the depreciation rate that the annual cost is greater than before, and in addition we have the liability to break down and put out the lights suddenly.

For example, if for 1000 lights we have two dynamos running at low speed, and costing £500 each, the total first cost will be £1000, and we may take the interest at 5 per cent. and depreciation $2\frac{1}{2}$, which will make the total annual cost of the dynamos themselves $7\frac{1}{2}$ per cent. on £1000, or £75 annually.

Now let us suppose that we double our speed; we shall be able to do with only one dynamo, and the total first cost will be only £500. We may take the interest as before at 5 per cent., but the depreciation will not be less than 15 per cent., making the total annual cost of the dynamo itself 20 per cent. on £500, or £100 annually.

Further, it must be remembered that the dynamos do not represent more than about 20 per cent. of the whole cost of an electric light plant (i.e. boilers, engines, dynamos, mains, &c.), so that a saving of half the cost of the dynamos only

saves 10 per cent. on the whole cost. On the other hand, the dynamo is the very heart and lungs of the whole system, and any defect in it will render the whole system useless.

For all these reasons I am of opinion that the speed of dynamo should be limited by mechanical considerations to one that will not rattle or shake it, or raise the depreciation above a very low annual rate.

It must be remembered that dynamo machines in no way differ from other machines absorbing horse-power, and that when a large horse-power is being received by any machine, that machine must be of a certain size and strength to stand the strain caused by it. In order to remind himself that the driving of dynamos is subject to the same conditions as the driving of other machinery, the engineer would do well to consider what would happen if in the dynamo that he has designed the moving coils were removed, and a wheel retarded by a brake substituted, the brake being so loaded that if the wheel were running at the same speed as the wheel carrying the coils would have done, the same horse-power would be absorbed as would be absorbed in the dynamo.

He will further do well to make his dynamo a good deal stronger than would appear to be necessary even under these conditions.

CHAPTER XII.

SOME TYPICAL ALTERNATING-CURRENT MACHINES.

THE DE MERITENS MAGNETO-MACHINE.

THE first machine which we shall describe is the magneto machine of M. de Meritens. The machine consists of one

Fig. 75.

or more rings carrying coils, revolving between the poles of permanent steel magnets.

Fig. 75 shows a one-ring machine of this form.

The coils consist of iron cores wound with wire of the form shown in fig. 76. They are mounted on a light brass

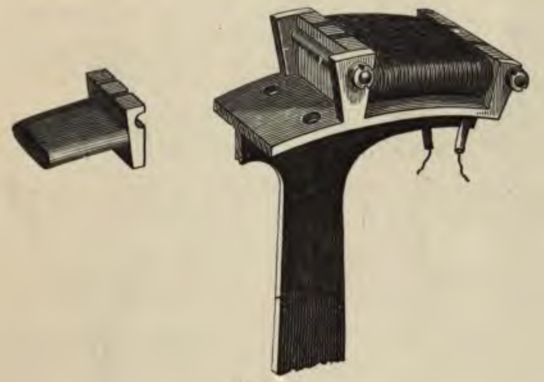


Fig. 76.

ring, and are held to it by brass pins which pass through the lugs and through grooves in the ends of the cores, as shown in fig. 76, so that the cores do not touch each other, but are magnetically insulated. When the machine is at rest, there is a magnet-pole of alternately opposite name over each junction, as seen in figs. 75 and 77. As the wheel revolves, the

Fig. 77.

polarities of the cores are constantly reversed, and currents are therefore induced in the wires.

Plate XVII. shows a De Meritens machine with five rings. We note that the magnets are here placed radially instead of parallel with the shaft, as in fig. 75.

Fig. 78 is a section through the five-ring machine, showing the general arrangement.

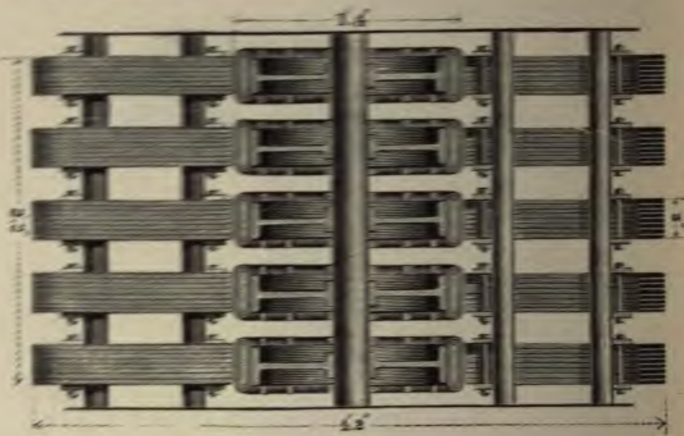


Fig. 78.

A reference to figs. 75 and 77 shows us that by means of the projecting ends of the cores, the latter are brought very close to the poles of the magnets, and so the latter can exercise their maximum effect.

The Cores.

The cores consist of a great number of plates of very thin sheet iron, lightly welded together, so as to form a solid block the full size of the coil. Iron is then cut away by suitable machinery, so as to form the wire space. The softer the iron of an armature core is, and the more separate strips it consists of, the more easily it reverses polarity. Each strip must be the full length of the core.

The Connections.

The wire is wound in the same direction round all the coils, but as the polarity of the cores is alternately in opposite directions, the directions of the currents induced in

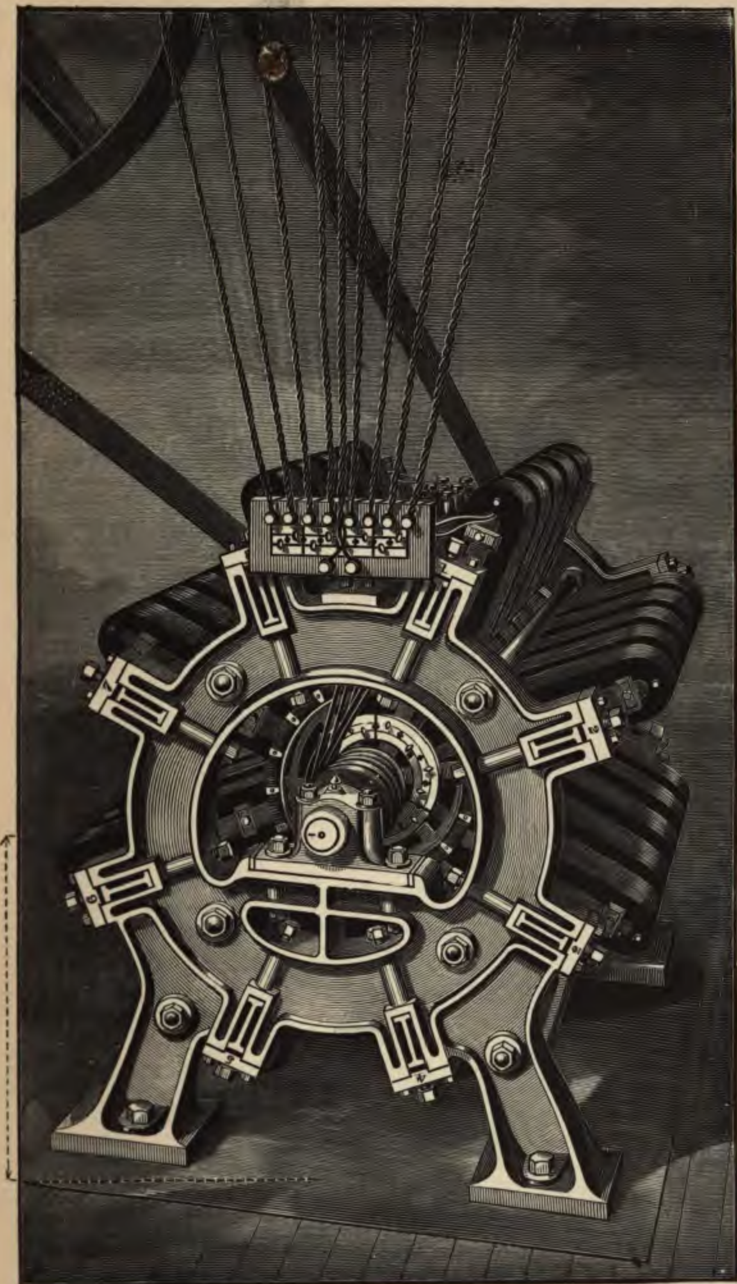


PLATE XVII.—THE DE MERITENS MAGNETO MACHINE.

neighbouring coils are in opposite directions, and consequently the connections have to be made as in fig. 79.

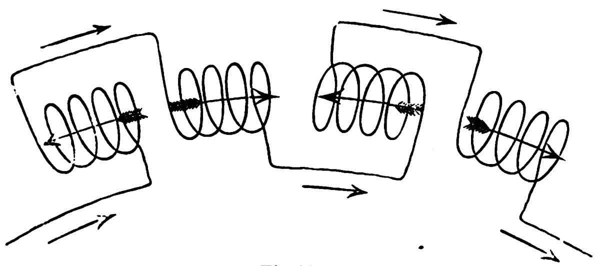


Fig. 79.

By means of a plug-board which revolves with the wheels, and which is seen in Plate XVII., the coils can be grouped in series, quantity, or any combination of the two, according as to whether currents of high or low E.M.F. are required.

The currents are taken off by means of springs pressing on metal rings revolving with the shaft, but insulated from it, and connected to the different rings of coils respectively. The large machine will thus feed five separate circuits, or any two or more of the circuits can be connected into one.

The De Meritens machine is excellent in working, and its construction is good both mechanically and electrically; its first cost, however, is very heavy. It is much used for lighthouses, where first cost is unimportant, and where its extreme simplicity and non-liability to break down recommend it.

The Siemens Alternating Machine.

The Siemens alternating machine, fig. 80, consists of two fixed iron rings carrying electro-magnets. These magnets are excited by a small auxiliary direct-current machine. The polarity of the magnets in each ring is alternately N. and S., and the polarity of each is opposite to that of the magnet opposite to it on the other ring. Each magnet has an extended flat pole-plate, as shown.

Between the two rings of magnets revolves a wheel, partly of wood, partly of metal, carrying in its circumference a number of coils equal to the number of magnets

in each ring. As the wheel revolves, currents are induced in these coils in the manner explained in page 134. The currents are taken off by springs and insulated contact rings in the same manner as in the De Meritens machine.

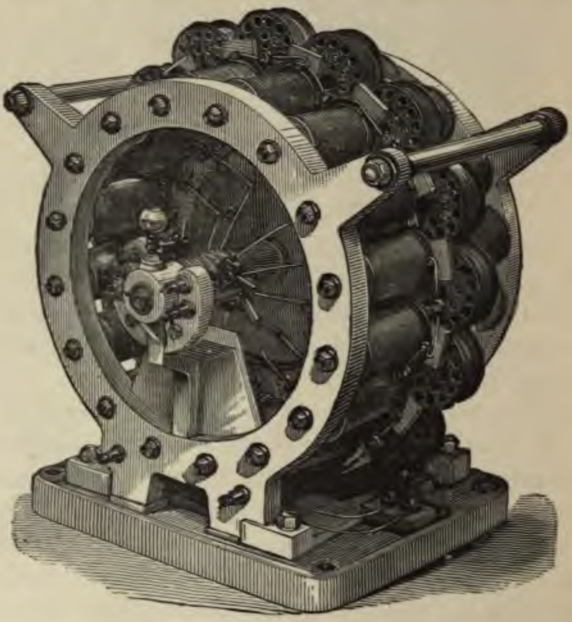


Fig. 80.

The coils have no iron cores, and are wound in brass bobbins, whose flanges are perforated with holes to check the circulation of currents in them.

THE FERRANTI MACHINE.

The Ferranti machine externally resembles the alternating Siemens, that is, the two rings of fixed magnets are similar to those of the Siemens machine, but the revolving armature is different. Instead of a number of coils of wire fixed to the rim of a wheel, it consists of a continuous zigzag of copper ribbon arranged as in fig. 81, so that the alternate radial portions are opposite poles of alternate polarity. Thus the E.M.F.s in alternate portions point to and from the centre of the machine alternately, and therefore are at

any instant all in the same direction in the ribbon. Half way between each pole the current reverses, and so an alternating current is produced at the contact rings, where it is taken off in the same manner as in the De Meritens and Siemens machines.

No iron is used in the armature, and the latter being very thin, the opposed magnet-poles can be brought very close together, and so the field of force is very intense.

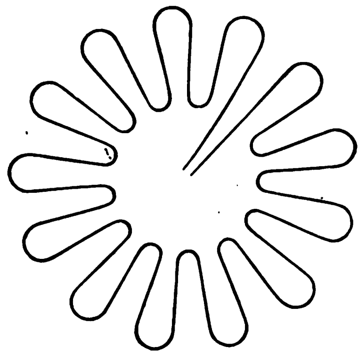


Fig. 81.

The machine is driven at an enormous speed, up even to 2000 revolutions per minute, and consequently the quantity of electricity produced by a machine of a given size is very large.

The design of the machine is, however, essentially an electrician's design as opposed to an engineer's design; electrically the machine is admirable, mechanically I venture to think that it is impracticable.

It is an essential point of the electrical design that no metal other than the copper ribbon should move through the magnetic field. This prevents the ribbon being supported on a metal wheel, and thus all the centrifugal force and vibration consequent on the high speed, and all the tangential pull consequent on the concentration of a great deal of horse-power in a small space, have to be borne by a zigzag copper ribbon, covered with a more or less soft insulator, and tied on to a wooden hub.

In discussing dynamo machines our critical faculties are apt to be blunted by a half-acknowledged belief that electrical forces, being different to forces which we have been accustomed to, are also unique in their relations with ordinary mechanical forces. This is not the case, and the right way to criticize the construction of a dynamo is to consider what would happen if it were run at its full speed without the magnets being excited, and a mechanical retarding force, such as a brake, applied to the moving coils, requiring the same horse-power to overcome it as the electrical energy which the machine is intended to generate.

I do not pretend to say that very high-speed dynamos, even with wooden wheels, may not work, and work for a considerable time, without breaking down, but I consider that such machines cannot be trusted for large plants or for central station work. It is not sufficient to be able to say that a machine will probably be safe, but it is absolutely essential that a break-down should be impossible.

To satisfy this condition I believe that slow speed is essential, and that wrought-iron, steel, or phosphor-bronze are the only materials which are admissible in the construction of the wheel which carries the moving coils.

The Gordon Machine.

I have therefore constructed a machine in the design of which I have endeavoured to keep the above conditions in my mind. As to the correctness of these views I can only say that after fifteen months' experience of the machine, I have reason to be satisfied with its performance, and that my opinion is daily strengthened that it is only by the use of colossal machines that electric lighting on a serious scale can be carried out, though I would not for a moment deny that numbers of small machines work very nicely when doing small work.

In these machines the magnets revolve and the coils are fixed. This alteration of the ordinary practice has been resolved on for three reasons. First, as the magnetic field

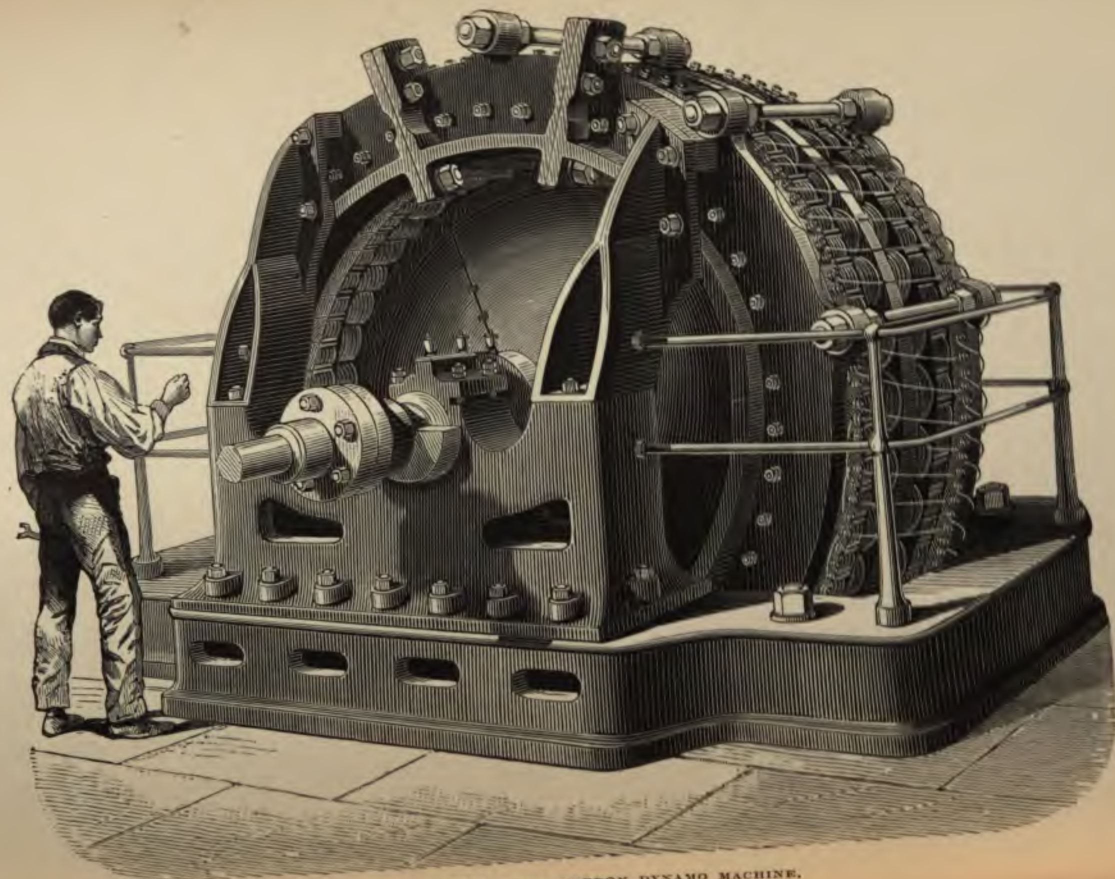


Plate XVIII.—The Gordon Dynamo Machine.

revolves with the moving wheel, instead of the latter passing through it, the wheel can be made of massive wrought-iron plates, thus giving great strength and freedom from vibration.

2nd. The armature coils being fixed, the current is taken off without rubbing contacts, which latter are always a source of trouble with powerful currents.

3rd. The heaviest part of the machine revolves, and so acts as a very efficient flywheel, keeping the light steady, in spite of slight irregularities in the engine. Two sizes of the machine have as yet been constructed, the eight-foot machine, which it is calculated will, with sufficient steam-power, work 5000 lights of twenty candles each, and the two-foot machine, which works 800 to 1000 lights without any undue strain. The machines are made in the works of the Telegraph Construction and Maintenance Company, at Greenwich.

THE EIGHT-FOOT MACHINE. (Plate XVIII.)

This machine was the first constructed; it consists of a wrought-iron wheel, carrying the magnets, which is eight feet diameter at the magnet centres (8 ft. 9 in. over all). The magnets, which are thirty-two in number, consist each of a cylindrical core of soft wrought-iron, which passes right through the wrought-iron disc, and projects equally on both sides of it.

Brass bobbins, containing the magnet wire, are slid on to the projecting portions of the cores, and are kept in their places by the pole plates, which are afterwards attached. The revolving wheel is built up of sheets of boiler-plate rivetted together, and strengthened by two cones of boiler-plate, placed one on each side. The cones and disc are separated by cast-iron distance-pieces, as shown in section in fig. 82.

This wheel revolves between two fixed iron rings carrying the armature coils.

Each ring carries twice as many armature coils as there are magnets on the ring. The reason of this is the following: In an early model which was made of the machine the

number of armature coils on each ring was made the same as the number of magnets. It was then found that the mutual induction of neighbouring coils very greatly diminished the output, i.e. that if one coil was at work, and then the coils on each side of it were set to work, that the output of the first coil was reduced by nearly fifty per cent.

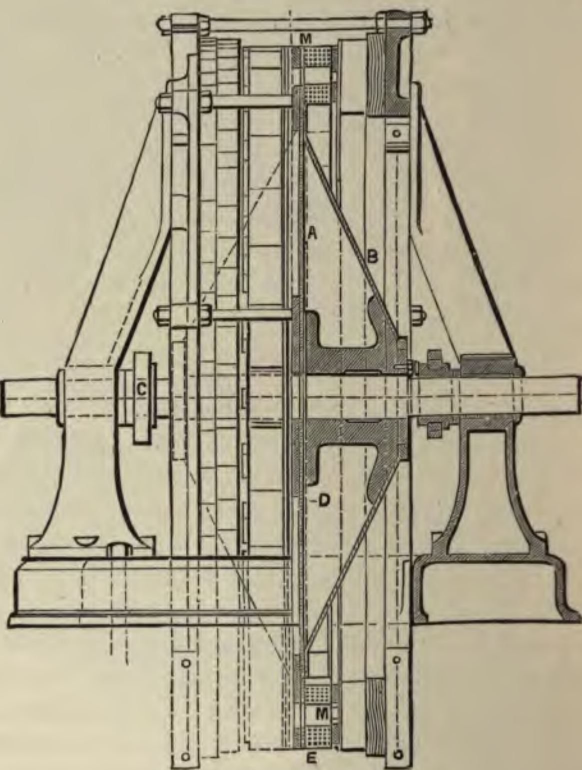


Fig. 82.

The reason of this was that the currents in the neighbouring portions of adjacent coils were in the same direction, and hence diminished each other by their mutual induction, in the same way that the currents in different windings of the same coil diminish each other by self-induction.

The plan now adopted (of making the number of armature coils double the number of the magnets) obviates this defect, as at any instant when the coils 1, 3, 5, &c., numbering round the circle, are producing their maximum current, the coils 2, 4, 6, &c., are idle. Immediately afterwards the coils 2, 4, 6, &c., will be at work, and 1, 3, 5, &c., idle, and thus each two active coils are always separated by an idle one which, partly by the space it occupies and partly by its shielding action, so reduces the mutual action of the coils on either side of it, as to render it inappreciable. Their actions on the intermediate coil are equal and opposite, so produce no current or change of current in it.

The fixed coils are secured to cast-iron frames, but the cores are prolonged, so that the frames are set back into a field of weak magnetism. Fig. 83 shows some of the fixed

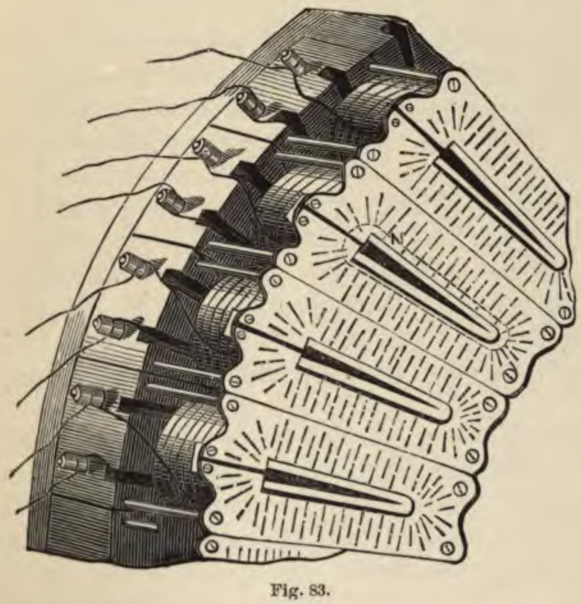


Fig. 83.

coils. Their flanges are made of German silver to check the circulation of currents in them.

The eight-foot machine runs at 140 to 180 revolutions per minute, and so is connected direct to the steam-engine

without belting. The total weight is twenty-two tons, and the total weight of the revolving magnet wheel seven tons. The only rubbing contact is that where the exciting current produced by two Burgin machines enters the revolving magnets. The method of regulation will be given in chapter XIV.

CHAPTER XIII.

SOME TYPICAL DIRECT-CURRENT MACHINES.

I. The Gramme Sub-Type.

The Crompton-Burgin Machine.

One of the best machines of the Gramme sub-type, now in practical use, is that invented by Mr. Burgin, and improved upon by Mr. Crompton. Plate XIX. gives two views of one of these machines of the size which works eighty 20-candle incandescent lamps, or four large arc lamps.

The revolving portion of the machine is shown at the bottom of Plate XX. It consists of four or more Gramme rings mounted on the same shaft, each consisting of a coil of iron wire of a hexagonal shape. The copper wire is wound on the flat portions of each hexagonal ring, leaving the corners bare, and more layers are wound at the centre than at the ends of each side.

Thus a line drawn round the ring outside the copper wire is very nearly circular. In Plate XX. one side of one ring has been shown without any wire on it for clearness. The rings are so fixed on the axis, that each gains a little on the next one, so that lines joining corresponding angles of the hexagons would form spirals.

The collector, seen on the left of the lower figure in Plate XX., and also in the centre of the lower figure in Plate XIX., consists of a great number of strips of copper, insulated from each other and fixed on an insulating barrel.

Each metal strip is attached to the corresponding portions of the coils of copper wire on each of the four rings. The current is collected by means of the brushes seen in the lower figure in Plate XIX.

The magnets, which also form the framework of the machine, are shown in the upper figure of Plate XX. They are of cast-iron, and the upper and lower portions are cast separately. The two portions having been bolted together, the cylindrical part in the centre, in which the armature to revolve is turned or bored true.

The arms of the magnets are wound with wire, as shown in Plate XIX., and so connected that one of the circular segments is a N. pole, and the other is a S. pole.

The bearings in which the shaft runs are carried by frames of brass or other non-magnetic metal, screwed on to the ends of the pole-pieces. These bearings are made whole, and not in two halves as in most machinery.

In putting the machine together, the magnets are first bolted together, then the brass at the collector end is screwed on. Next, the revolving armature is slid in from the other end, and the collector end of the shaft slid into its bearing.

Then the second brass is slid over the pulley end of the shaft and bolted to the pole-pieces, and last of all the pulley is put on and secured by a set-screw pressing on the flattened end of the shaft.

The collecting brushes are carried by a moveable arm, which can be turned round the bearing at the collector end of the machine, the outside of the brass being turned true for the purpose. It can be clamped at any angle by a set-screw, seen just below the end of the shaft in the lower figure of Plate XIX.

The reason of having this adjustment is that the points where the E.M.F.s of the two halves of the ring meet (P N, fig. 71, page 140) are not the symmetrical points shown in that figure, but, by reason of the appreciable time taken to change the magnetism of the iron cores of the revolving rings, are displaced forward,* and the brushes have to

* "Forward" means in the direction in which the armature is revolving.

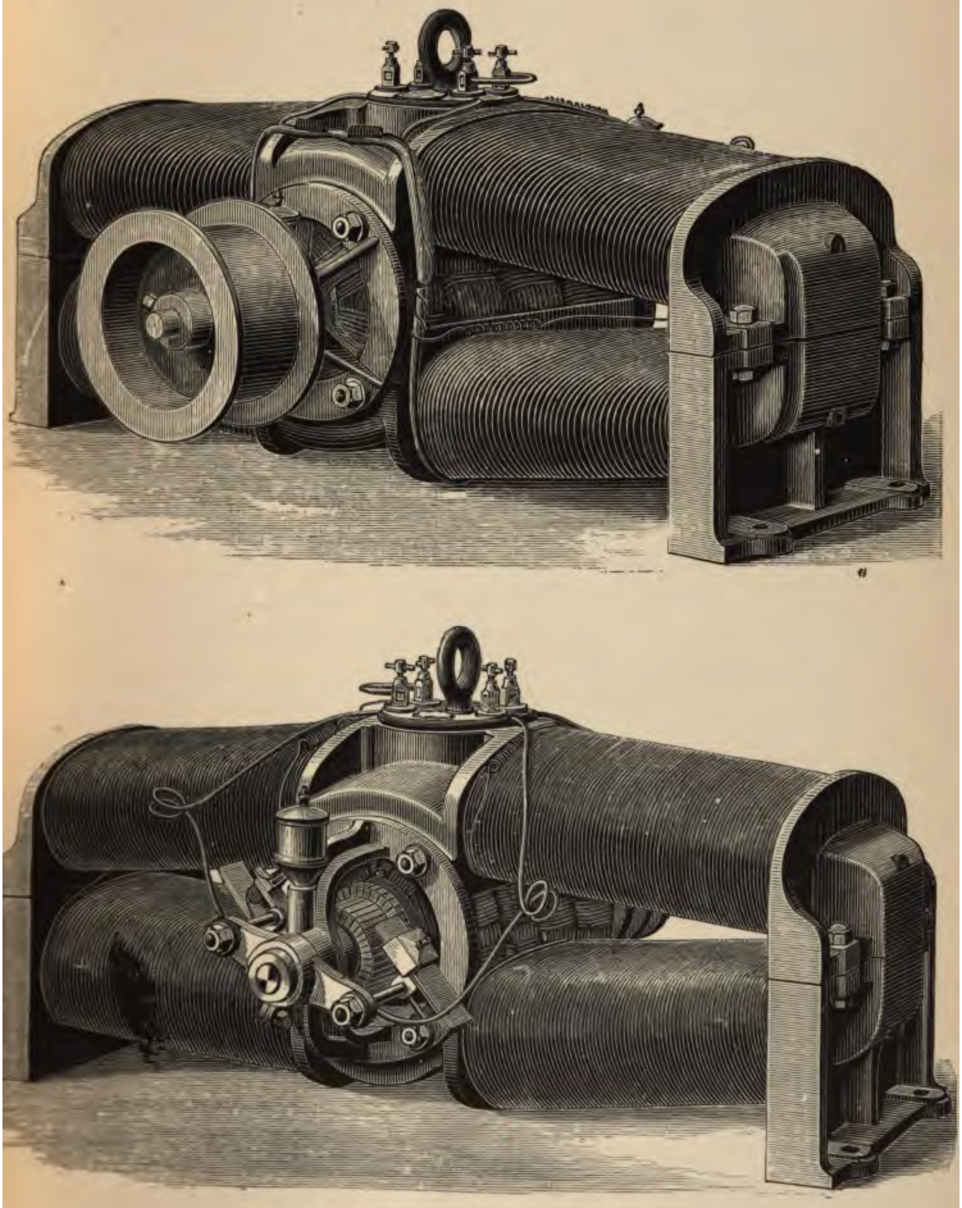


PLATE XIX.—THE CROMPTON-BURGIN DYNAMO MACHINE.

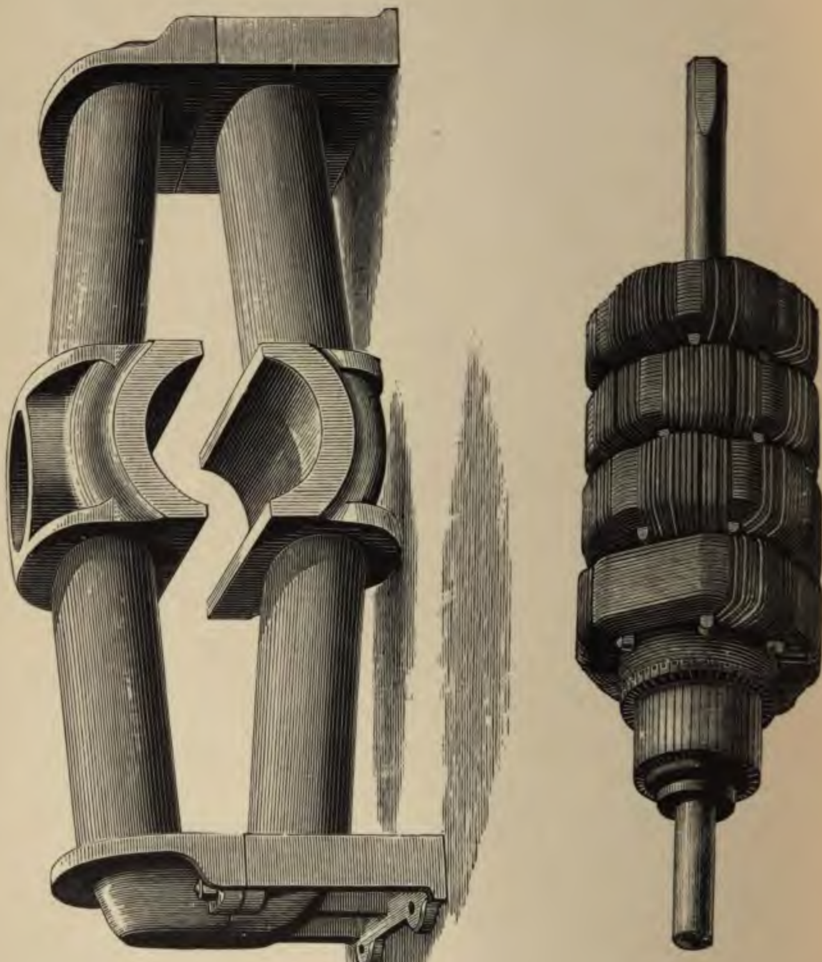


PLATE XX.—THE CROMPTON-BURGIN DYNAMO MACHINE.

be moved forward to follow them. These points, which are the points of least sparking, have to be found experimentally, by moving the brushes while the machine is running. This can be done by means of the arm we have just described.

The brushes consist of a number of strips of thin sheet-copper about two inches wide, which are held in a brass frame. They slowly wear away, but can be pushed forward by loosening the clamp screw at the back of the holder shown in the lower figure of Plate XIX., and when consumed can be renewed at small expense.

The brushes are pressed upon the collector barrel by means of springs, and can be lifted off it when the machine is not in use by means of little levers.

The rods carrying the brushes are insulated from the adjusting arm, and are connected to the terminals at the top of the machine by means of flexible wires.

These machines are wound "series," "shunt," or "compound,"* according to the work for which they are intended, They run at 1600 revolutions per minute.

The working of these machines is extremely satisfactory, the only repairs which they require are due to the fact that the sparking, which is incident to all direct-current machines, is apt to wear the collector barrel into grooves. I find it advisable, when these machines are in nightly use, to take out the armature and place it in the lathe about every two or three months, and to take a very light cut over the collector barrel with a sharp-pointed tool.

The Brush Machine. (Plate XXI.)

This machine may be considered as a development of the Gramme sub-type, but differs from the Gramme machine in many important particulars.

The revolving armature consists of a wrought-iron ring, figs. 84 and 85, round which the wire is wound in the hollow channels seen in fig. 84, so that it forms the coils seen in fig. 85. The iron between the coils comes up close to the magnet-poles, and so receives an intense magnetism. The

* See Chap. XIV.

Fig. 84.

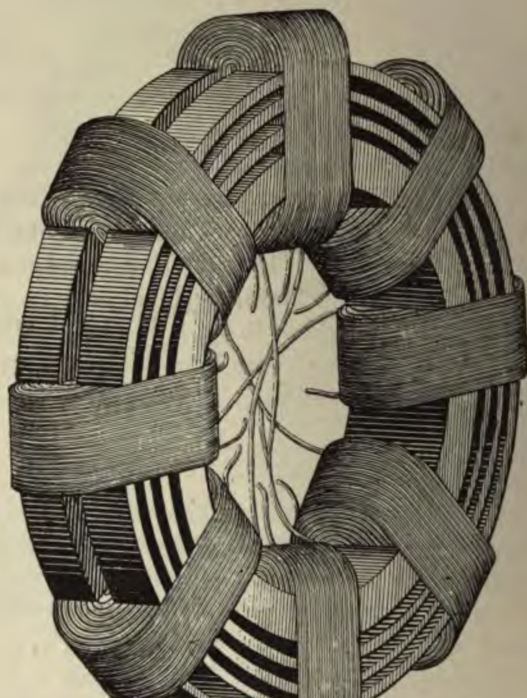


Fig. 85.

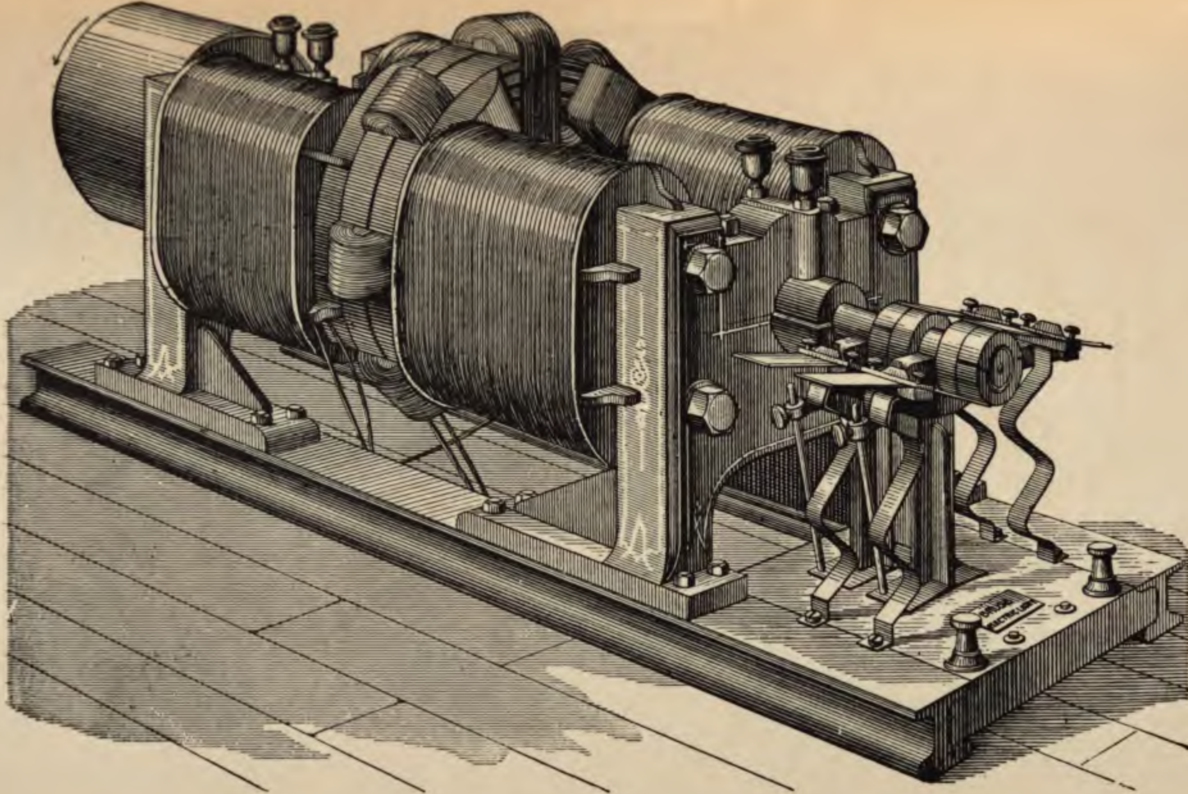


PLATE XXI.—THE BRUSH DYNAMO MACHINE.

annular channels are cut to prevent the circulation of currents in the iron itself.

The ring is mounted on spokes and on a hub of German silver (not shown in the figs.), the high resistance of which prevent the induced E.M.F.s making serious currents in it.

It revolves between magnets with extended pole-pieces, as shown in Plate XXI., the two opposed poles at the same side of the ring being of the same name.

So far the machine is closely allied to the Gramme, but the method of collecting the currents is peculiar to itself.

In the machine we are now discussing, the coils are eight in number, and each is connected in series to the one opposite to it, i.e. at the other end of a diameter of the ring. Thus the eight coils form four separate circuits, each circuit having its own commutator.

The four commutators are arranged in two pairs, the two of one pair commutating alternate coils with the two of the other pair.

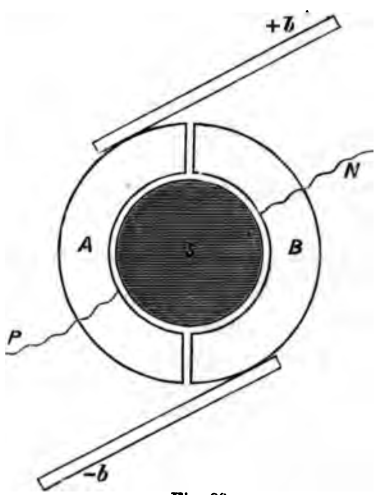


Fig. 86.

In the first machines designed, each commutator consisted of a pair of circular metal segments (A B, fig. 86) to which the two free ends (P N, fig. 86) of its coils were respectively attached. The brushes $+b, -b$ pressed on these rings.

As the armature ring revolves, the current in the coils 1, 1*a* (fig. 87) reverses twice each revolution, and at the moment of reversal the segment A (fig. 86), which was in contact with the positive brush (+*b*), left it, and the segment B arrived at it, and hence the alternating current generated in the coils was received as a direct current in the brushes +*b*, −*b*.

Close to the segments A B (fig. 86) on the shaft attached to the coils 1, 1*a* (fig. 87), were a similar pair of segments, which

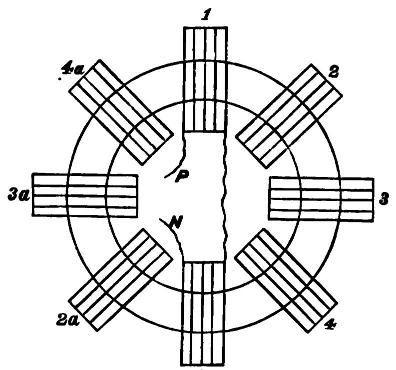


Fig. 87.

we will call A′ B′, attached to the coils 3, 3*a*. The division line of these segments was at right angles to the division line of the first pair.

The brushes +*b*, −*b*, are wide enough to rest on both pairs at once. When the machine is working, the current in each pair of coils commences as the coils leave the neutral point, rapidly reaches its maximum, and continues steady till the coils approach the neutral point at the other side, when it again rapidly falls to zero. Thus the wide brush connects the coils 1, 1*a* and 3, 3*a* "in quantity," and as the current in one is at a maximum while the other is a minimum, the total current has a nearly constant value.

Here, however, a difficulty occurred. When one pair, say 1, 1*a*, were in the maximum position, there was hardly any E.M.F. being induced in the other pair, 3, 3*a*, and as they were connected in quantity with the first pair, they

formed a shunt to the lamps, and allowed a back current to flow through them from the active coils connected with them.

To get over this difficulty, Mr. Brush shortened the seg-

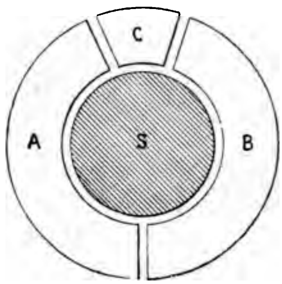


Fig. 88.

mental pieces A B of the commutators, and introduced the insulated piece C (fig. 88).

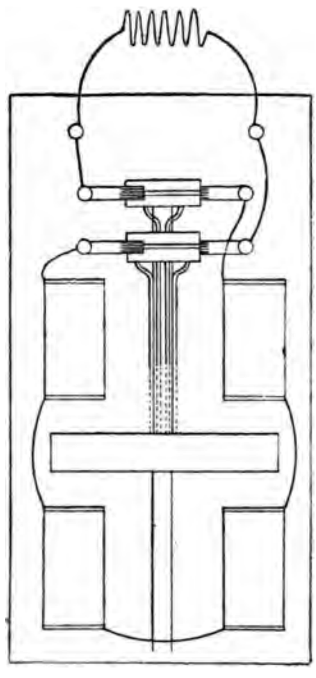


Fig. 89.

This piece is commonly made of copper to ensure even wear of the whole commutator cylinder, but as it is insulated

and not connected to anything, it may be considered as an insulator.

The effect of it is, that as each pair of coils passes the neutral points, and the E.M.F. in it falls to zero, that pair of coils is insulated and cut out of circuit, and the other pair, which is in quantity with it, and which at that moment has its maximum E.M.F., works alone. This entirely gets rid of the back currents.

A second precisely similar pair of commutators is connected to the coils 2, 2*a*, 4, 4*a*. The two pairs of commutators, each with their brushes, are seen at the right hand end of the shaft in Plate XXI.

The two circuits thus formed are usually connected in series, so as to form one of double the E.M.F. of each.

The magnets are also connected in series with the circuits. Fig. 89 is a general diagram of the connections.

These machines are very successful as high-tension machines for arc-lighting, as machines of 2000 volts E.M.F., maintaining 40 arcs in series, are in regular work.

For some reason, however, the inventor has not been successful in making low pressure machines on this principle for incandescent lighting.

II. The Siemens Sub-Type.

The Siemens Machine.

The revolving portion of the Siemens machine (fig. 90) consists of an iron cylinder, round which wire is wound *longitudinally*, i.e. so that the wire is parallel to the axis. The collector is similar to that of machines of the Gramme sub-type, and consists of a number of strips of metal fixed on an insulating barrel.

The wire forms a continuous coil or closed circuit, and wires are led sideways from it at intervals to the commutator strips.

The magnets are made of bars of wrought-iron, straight at the ends and curved in the middle. The current in the magnetizing coils has such directions, that the whole of the portion of the magnets at the top of the machine

has one polarity, and that at the bottom of the machine the opposite. The outer ends of the upper and lower magnets, which are of opposite polarities, are connected by yoke-plates in the usual way.

We notice that the machine shown in fig. 90 is

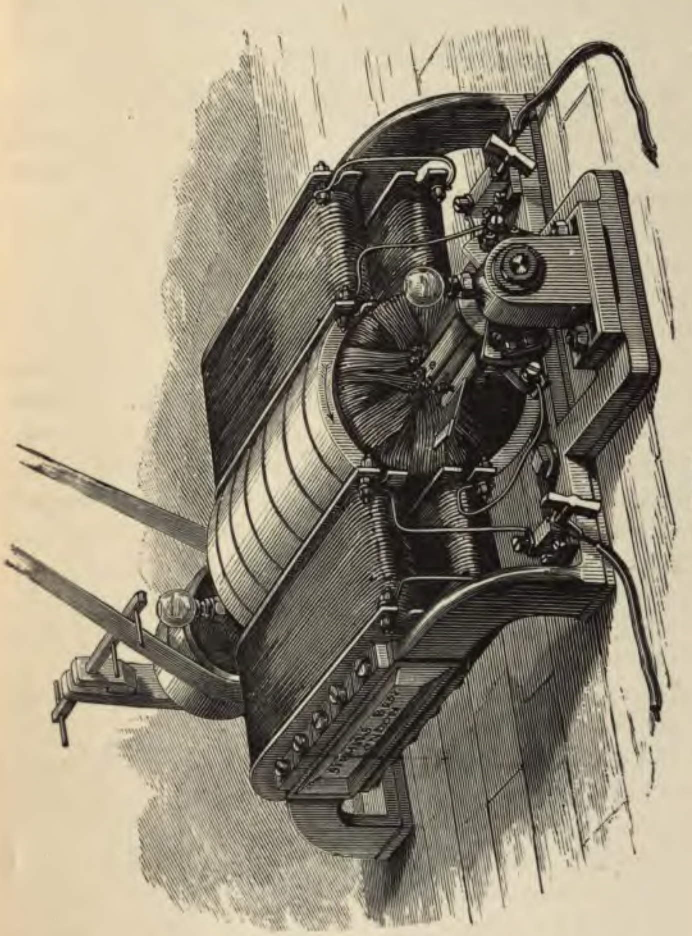


Fig. 90.

lifted off the ground by legs. The reason of this is, that if it were to be allowed to go flat on the ground, and were laid on an iron floor, the latter would make a magnetic connection between the centre and ends of the

lower magnets, and would greatly weaken the magnetism of the latter.

These machines are often made vertical, i.e. to stand on one end. They then occupy less space, and there is no danger of accidental magnetic communication being made between their poles.

THE LARGE EDISON MACHINE. (Plate XXII.)

The armature of this machine consists of a number of discs of thin iron plate, separated by paper so as to form a barrel 3 feet 6 inches long. A number of copper rods are laid on the circumference of this barrel, parallel to its axis. The diameter of the barrel outside the bars is 28½ inches.

It is necessary to connect the bars, so that they may form a continuous circuit analogous to the longitudinally-wound wire in the Siemens machine. This is accomplished by means of a number of copper discs, equal to the number of bars; each disc has two lugs projecting from it. Half the discs are put at each end of the barrel, and are set so that the lugs form in each case a spiral line round its end of the barrel, the two spirals being in the same direction. The bars are then connected from lug to lug, so that the current goes along one bar across a disc, back along a bar at the opposite side of the barrel to the first, then across a disc at the opposite end of the barrel to the first disc, and then along the bar next to the first bar, and so on.

The copper discs are connected respectively to the different commutator bars.

The whole barrel is bound round and round with steel wire to keep the bars from flying out under the action of the centrifugal force.

The whole barrel revolves between the poles of a very large electro-magnet.

These poles consist of immense blocks of cast-iron, which nearly meet, but are kept apart by the brass distance-piece seen in the front of Plate XXII.

The lines of force leaving the magnets terminate in the central iron barrel. The construction of the barrel, i.e. its being built up of iron discs, insulated from each other, pre-

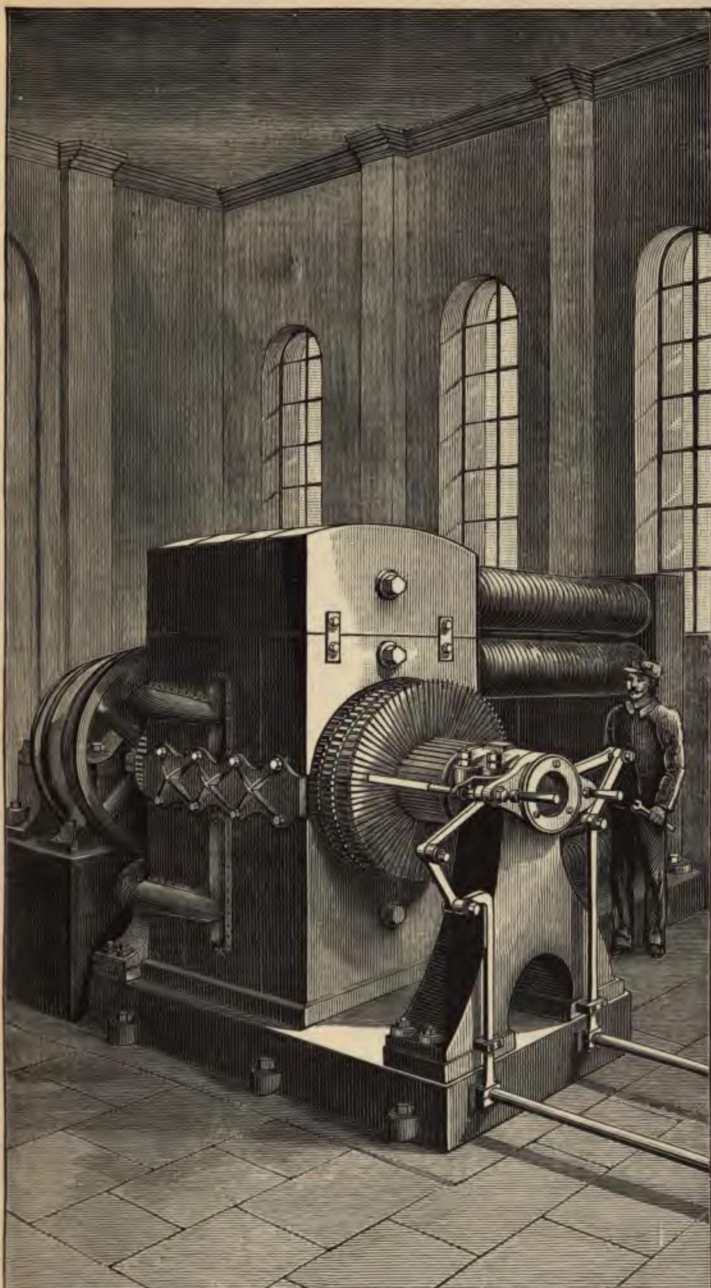


PLATE XXII.—THE EDISON DYNAMO MACHINE.

vents the circulation of currents in it. The armature is kept cool by means of a small smith's fan, the air from which is admitted by the pipes seen in the front of Plate XXII.

The magnet bobbins are twelve in number, and are each eight feet long. They are shunt wound.

The resistance of the armature is ·00049 ohm, and that of the magnets 21 ohms.

The machine will maintain 1000 to 1200 lamps of 16 candle-power. Its total weight is about 25 tons.

The Edison Company also make small machines which work well.

CHAPTER XIV.

REGULATION OF MACHINES.

If the number of lamps on a dynamo machine be altered, the electromotive force will alter, and the brightness of the lamps will also alter. Generally speaking, if the number of lamps be diminished, the E.M.F. will increase, and *vice versâ*.

This change of E.M.F. is not admissible in practical work, and has to be corrected by various methods.

These methods differ according to the nature and size of the dynamo. With large dynamos, for instance, we can afford to govern by hand, as the wages of the man employed are distributed over a very large number of lamps, and hence the additional cost per lamp per annum caused by his wages is trifling.

With small dynamos, however, the man's wages would be distributed over only a few lamps, and hence the increased cost per lamp per annum would be very great.

For instance, to hand-govern a machine working fourteen hours daily will require two men, whose wages together would amount to, say, £120 per annum.

Let us assume that the rest of the expense amounts to £1 per lamp per annum, then with a 5000-light machine these wages would amount to $\frac{120 \times 240}{5000} = 5\frac{3}{4}d.$ per lamp per annum, an insignificant addition to £1; but if we have only a 250-light machine, these wages per lamp per annum will be $115d. = 9s.\ 7d.$ per lamp per annum, an increase of nearly 50 per cent. on the £1.

Thus, while large machines may be hand-governed, in

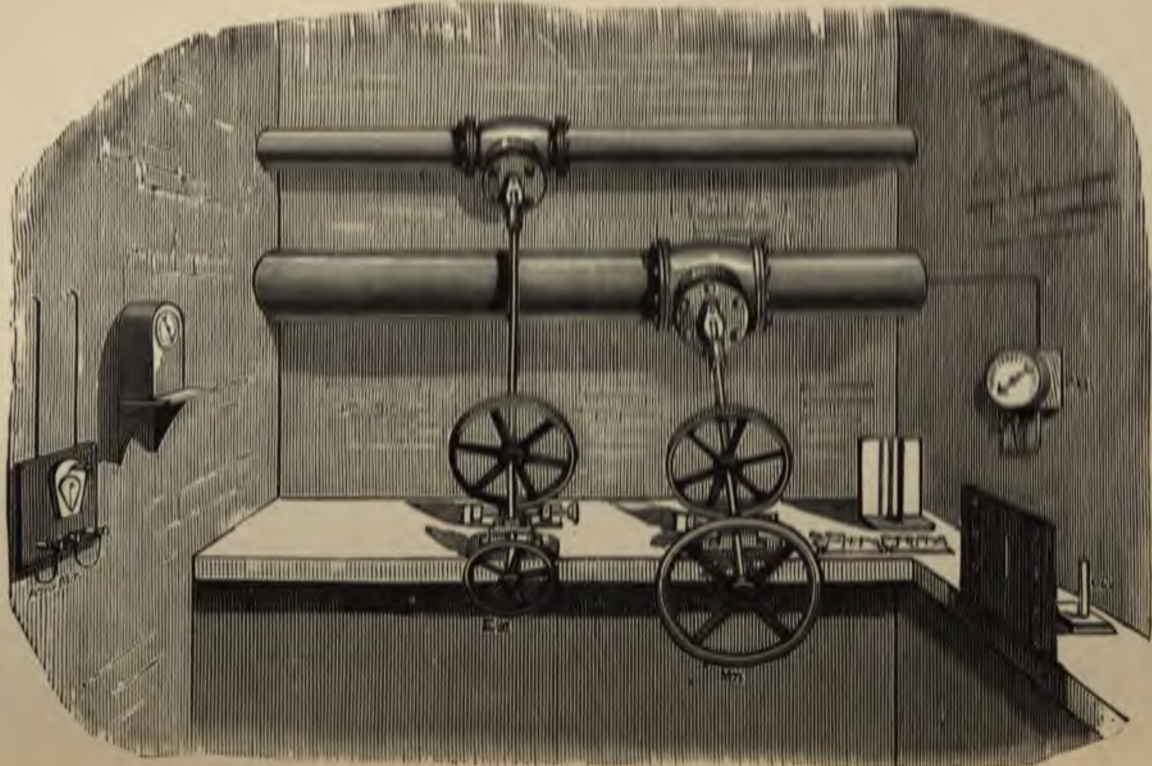


PLATE XXIII.—APPARATUS FOR REGULATING THE GORDON DYNAMO.

small machines it is necessary to put up with much unsteadiness in the light in order to use automatic methods of governing, none of which, as far as my present experience goes, are equal to hand-governing.

The following is the method I adopt for governing my large dynamos.

It will be remembered that the large machine is driven by one steam-engine, and the "exciting" machine by a smaller separate one.

A dark room (Plate XXIII.) is provided near the engines, and the steam-pipes pass through it. The large steam-pipe supplies steam to the big engine; the small one supplies it to the exciting engine.

The large engine has an ordinary governor on it of the Porter type, and the large stop-valve is opened wide, so that the governor takes charge of the large engine.

The small engine is then started slowly, and the lights begin to glow, and the speed is increased till they are at their right candle-power, as shown on the photometer* at the right of Plate XXIII.

In case of a number of lamps being turned off, the brightness of the rest rises somewhat, and the man in charge slightly closes the valve of the small engine, reducing its speed until the light is right. To assist him in making a slight motion, a tangent screw is attached to the axis of the valve wheel. This screw can be instantly thrown out of gear on removing a wedge, if a large motion is suddenly required.

With a large system, such as is worked by one of these dynamos, the maximum number of lamps which are controlled by any one switch form a very small percentage of the whole number at work, and consequently there is ample time to adjust the pressure and compensate a change of brightness step by step, so that it never reaches an amount which can be seen without a photometer.

One dynamo has been successfully regulated by this method for fifteen months.

* See Chapter XVIII.

On the right of Plate XXIII. is seen a steam gauge for showing the boiler pressure, and on the left is a strophometer for showing the speed of the large engine, and an ammeter for showing the strength of the exciting current. The ammeter is ordinarily short-circuited by a spring key seen below it. On pressing the button the short-circuit is broken, and the whole current flows through the ammeter.

Automatic Electric Governors.

Various attempts have been, and are being made to do automatically what is here done by a man, i.e. to vary the speed, either of the exciting engine when two engines are used, or of the main engines when the dynamo is self-excited, by means of some kind of voltmeter actuating the throttle-valve, so that just as an ordinary governor keeps the speed constant, so the electric governor would vary the speed so as to keep the E.M.F. constant.

The Willans Governor.

The only one of the various governors now being made which I am yet able to describe is the Willans governor, and even this is so lately completed, that I can give no results of its practical working, or say whether it or any other form are likely to be a practical success.

The following description of the apparatus is taken from *Engineering* of February 15, 1884:—

"The difficulty, hitherto, has been to get a power sufficiently large to be independent of the friction of the throttle valve, and still more, of that of the expansion valve, should it be desired to govern by varying the expansion instead of by throttling. Mr. Willans, instead of actuating the throttle valve or expansion valve directly by the electro-magnet or solenoid, employs the latter to actuate a small supplementary valve, which is almost frictionless, and this in its turn controls the supply or discharge of water, steam, or other fluid pressure to a cylinder in which a piston works, which actuates the throttle valve or expansion gear of the engine. In this way, although absorbing a power less than

half that required for one 20-candle Swan lamp, the solenoid is able to control the most powerful expansion gear.

"The Willans electric governor is shown in fig. 91, where S is a solenoid taking the place, in incandescence lighting, of one of the lamps. In other words, the solenoid is on a branch between the main wires. The core C of the solenoid is suspended by a spring, and this spring is attached at the top to an adjusting screw used for regulating the light. The other end of the core is connected with a small piston valve working inside the main piston W, which latter piston controls the throttle valve in the casing T. Water or other fluid pressure is admitted by the pipe P into an annular chamber surrounding the water piston W, and also by means of a suitable passage X, into an annular space between the two small pistons which form the piston valve. The water, after actuating the piston W, escapes through the pipe E, and by means of a small piece of flexible pipe not shown. The action is as follows:—

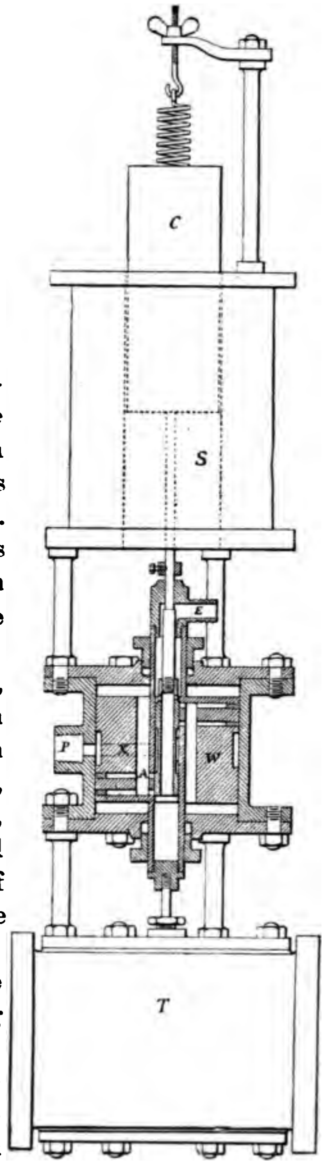


Fig. 91.

"When the electromotive force is constant, the pull of the spring balances the pull of the solenoid coils on the core C, but if the electromotive force rises, on account either of an increase in steam pressure or because lights are turned out, the core C is drawn further into the coils of

the solenoid, and moves downwards, carrying with it the piston valve. The latter uncovers the port A, and admits water pressure from the annular space between its pistons to the upper side of the water piston W, which then travels downwards, following the piston valve. So soon as the electromotive force has, by the closing of the throttle valve and the consequent slowing of the engine and dynamo, become sufficiently reduced, the core C comes to rest, and W consequently overtakes the piston valve, and closing the port A, comes also to rest. When the electromotive force falls below the normal standard, the foregoing action is, of course, reversed. When lights are turned out or in one by one, or when the steam pressure rises or falls gradually, the action of the governor is, of course, exceedingly gradual, though it can be detected by measurement, but under any violent test, such as switching out a large proportion of the lights, it acts with great quickness. It will be noticed how the perfect action of such a governor is helped by the ingenious 'differential' movement of the two pistons, and by the locking action of the piston valve."

Compound Winding.

Another method of regulating, but which can only be applied to direct-current dynamos, is that known as *compound winding.*

The E.M.F. of a "series-wound" dynamo increases when more lamps are put on, i.e. when the external resistance is diminished, but the E.M.F. of a shunt-wound dynamo decreases under the same circumstances.

By winding the magnets partly with a thick wire connected in series with the armature, and partly with a thin one connected in shunt, it is possible, within certain limits, to keep the E.M.F. nearly constant, in spite of considerable changes in the number of lamps on the machine.

The proportion between the shunt and series wire has to be found experimentally for each type of machine.

The first approximation is made by taking the curves representing the respective rise and fall of E.M.F. with

increased number of lamps for shunt and series-wound magnets. A straight line to represent constant E.M.F. being drawn between the two curves, the areas on each side of it represent respectively the weights of each kind of wire required.

In spite of its apparent simplicity, I doubt if compound winding will be much used in the future, except for small machines, as it does not keep the E.M.F. quite constant, and the apparatus required for making the final regulation would equally well do it all.

Conclusion.

The true secret of successful regulation is to have very large dynamos, because then, as we have said before, the maximum number of lamps that can be turned out at one time is a very small percentage of the whole, and when there are a great number of lamps on one machine, the cost per lamp of regulating, either by hand or by an elaborate mechanical contrivance, is very trifling.

CHAPTER XV.

ON THE PROPOSED DISTRIBUTION OF ELECTRICITY BY SECONDARY GENERATORS.

WE have already stated (page 67) that the quantity of copper required to convey a certain quantity of electrical energy to a given distance with only a certain percentage loss depends, not on the energy but only on one factor of it, namely, the current, and, therefore, if with our given quantity of energy we can increase the electromotive force and diminish the current, we can use less copper.

If, for instance, a certain weight of copper is required to convey one electrical H.P. a certain distance with a loss of five per cent. at 100 volts pressure, then, if the pressure is raised to 1000 volts, only one-tenth of copper will be required for the same quantity of electrical energy.

Pressures much exceeding 100 volts cannot, however, be used for incandescent lamps (as at present constructed) which are required to be turned out singly, as higher pressures involve putting two or more lamps in series.

Further, the Board of Trade have very rightly forbidden the use in indoor wires accessible to the public of electricity at pressures exceeding from 150 to 200 volts, on account of the danger due to shocks which might be received from it.

Various attempts have been made to convey electricity at high pressures from the generators to the place where it is to be used, and there to convert it into low-pressure electricity before it goes to the lamps or other fittings inside the houses.

THE GOULARD AND GIBBS SYSTEM.

The most promising system for this purpose, when looked

at superficially, is that lately invented by Messrs Goulard and Gibbs, which may be briefly described as a system of inverted induction coils :—

The ordinary induction coil* consists of a coil of thick wire with an iron core, surrounded by another coil of fine wire.

A battery current of low pressure is sent through the thick wire, and is rendered intermittent by a "contact-breaker." At each intermittence an electromotive force is induced in each of the convolutions of the fine wire. As this wire has a great many turns and a high resistance, the "secondary current" generated will have small quantity but very high E.M.F. With the largest induction coils yet constructed, pressures of a million volts and over have been obtained.

In Nov., 1879, the late Mr. William Spottiswoode pointed out † that if the primary coil is excited by the current of an alternating machine instead of by a battery, no contact-breaker is required, and that greatly increased results are obtained.

The Goulard and Gibbs apparatus consists essentially of an induction coil, of which the *primary* coil consists of a long thin wire, and the *secondary* of a short thick one. An alternating current of small quantity but of high pressure is sent into the primary, and induces in the secondary a current of more quantity and less pressure, which can be used in the lamps. Messrs. Goulard and Gibbs' scheme is to place such an induction coil in each house, or group of houses, and to convey the electricity from the generator to the induction coil in the form of a high-pressure current, which can be carried by a fine wire, and so to save copper.

Efficiency.

It is obvious that there must be some loss in this as in any system of transformation. In particular, the whole of the energy required to send the primary and secondary currents through the true copper resistances of the primary and

* See my "Electricity," 2nd ed., vol. ii., page 107.

† See Phil. Mag., 1872, page 360, or my "Electricity," 2nd ed., vol. ii., page 124.

secondary coils respectively is wasted in heating these coils. The efficiency E of each induction coil is the ratio of the electrical energy generated in the secondary to that expended in the primary, and the percentage efficiency is:—

$$E_P = 100 \cdot \frac{E_2 C_2}{E_1 C_1} \quad . \quad . \quad . \quad . \quad (59)$$

where C_1, C_2 are the respective currents in the primary and secondary coils, and E_1, E_2 the respective E.M.F.s at their terminals.

Messrs Goulard and Gibbs have not yet published any figures as to the efficiency of their coils. Pending their doing so, we can, however, investigate what is the minimum value it must have, in order that the adoption of the system may reduce the first cost of an electric light plant.

The changes in the different items of first cost will be as follows:—

The total weight of copper will be reduced in the ratio $\frac{C_1}{C_2}$.

This will reduce the diameter of the wires in the ratio $\sqrt{\frac{C_1}{C_2}}$.

The thickness of the insulator must be increased in the ratio $\frac{E_1}{E_2}$; but, as the wire is smaller, the weight of insulating material will be increased in a less ratio than this.

The total cost of the rest of the plant, i.e. engines, boilers, dynamos, &c., will be increased in the ratio $\frac{100}{E_P}$.*

The cost will also be increased by the cost of the induction coils themselves.

Let us investigate a fairly typical case. We will suppose we have an ordinary plant costing £20,000 arranged to supply

* For suppose we lose 30 per cent. in the induction coil, or that $E_P = 70$, then a plant which can produce 1000 lights direct can now only produce 700, and to make it do 1000 it must be increased in the ratio $\frac{1000}{700}$.

electricity at 100 volts pressure; let us consider what the minimum efficency E_p of the induction coils must be, in order that we may provide plant for the same number of lights for the same money on the Goulard and Gibbs system with the primary E.M.F. raised to 1000 volts.

In the ordinary 100-volt system, the £20,000 may be approximately apportioned as follows in a moderately scattered district:—

Copper	£5,000
Insulator	2,000
Rest of plant (engines, boilers, dynamos, &c.)	13,000
Total . .	£20,000

On increasing the E.M.F. to 1000 volts, we alter the cost as follows:—

Copper	£500
Insulator, say	4,000
Induction coils, say	1,000
Leaves for rest of plant	14,500
Total . .	£20,000

In order that the plant which we can now afford may be able to supply the required quantity of electricity, the efficiency of the induction coils must not be less than—

$$E_p = 100 \cdot \frac{13,000}{14,500} = 89 \text{ per cent.}$$

I fear that it is not likely that the efficiency will be anything like so high as this. *It must further be remembered that the bill for coals will be increased in the ratio* $\frac{100}{E_p}$.

It would be necessary further, not merely that the plant should cost the same money, but that there should be a very great economy, in order to compensate for the extra risk run by the men in the engine-room, and men employed in street repairs, who might accidentally cut or break the primary wire, and who if they did so would probably receive a fatal shock.

On the other hand, in very scattered districts (as, for

instance, the stations on the Metropolitan Railway which are now being lighted on this system as an experiment), the proportion of the cost of the copper to that of the rest of the plant in a 100-volt system might be much greater than in the typical case which we have suggested, and in such a case the system might be useful. Each case where it is proposed to apply the system should, however, be investigated by the method given above and discussed on its own merits.

CHAPTER XVI.

THE "STORAGE" OF ELECTRICITY—SECONDARY BATTERIES.

The advantages obtained by the storage of gas in gasometers have suggested to many inventors the hope of storing electricity, or rather electric energy, in a similar manner.

The only way in which electric energy could be stored *directly* would be to insulate two conductors and to charge them positively and negatively respectively. On connecting them by a wire, a current would flow from one to the other through the wire until the pressures were equal. This wire might be interrupted by a lamp through which the current could flow.

The method is of course impracticable owing to the enormous size which the conductors would have to be in order to hold a charge large enough to produce an appreciable current even for a short time.

The two conductors may be arranged to form the plates of an ordinary condenser or Leyden jar,* in which case they will hold rather more energy than before, but still not enough to be of any practical use.

Seeing then that the direct storage of electric energy is impracticable, attention was called to the storage of other kinds of potential energy in a form which could be converted into electric energy when wanted. This potential energy may be generated in various forms, and the energy expended to produce it may be either electric energy or energy of some other kind.

* See my "Electricity," 2nd ed., vol. i., page 61.

For instance, the potential energy which we are storing ready to draw out in the form of electric energy may be the chemical energy latent in the zinc and acid of an ordinary voltaic battery, or it may be the mechanical and chemical energy respectively of the steam ready under pressure in our boiler, and of the coals lying ready to be shovelled into the furnace.

If it is desired to produce the potential energy, which is to be stored, by expending electric energy, then we may use a current to work a motor which is employed in compressing air or raising water to a height, so that the air or water could afterwards work a dynamo, or the current might be employed in producing chemical charges in a *secondary battery*.

SECONDARY BATTERIES.

M. Planté has found that if two sheets of lead properly prepared † be placed in diluted sulphuric acid, and connected respectively to the poles of a dynamo, that a chemical change takes place in them, which enables them to act as a voltaic battery until they have given off a quantity of electric energy forming a considerable percentage of that expended by the dynamo in "charging" them.

The process of preparing the lead being a tedious one, M. Faure invented a battery consisting of ordinary plates of lead coated with "nimium," or red oxide of lead; and in 1880, great excitement was caused in England by an announcement which appeared in the *Times* that "a million foot-pounds of electrical energy had been brought from Paris to London in a small portmanteau."

A million of anything seems to be a large quantity, but to get a true idea of the magnitude of a million foot-pounds of electrical energy, we may note that it equals ·377 of a commercial unit, and at the maximum price authorized by the Board of Trade for the St. James's district is worth 2·6*d*, say two-pence halfpenny.

An immense number of modifications and improvements of the secondary battery have been patented since the above

† See my "Electricity," 2nd ed., vol. ii., page 10.

date, but I have not as yet seen one which has worked with even reasonable success.

Even when new and freshly charged the percentage return is not very large, not more than about 75 per cent. at most, i.e. the energy given out is not more than 75 per cent. of that expended in "charging" the batteries.

Secondly, the batteries will not hold a "charge" for any length of time. I mean that, if charged and put away for a week, the return at the end of the week is much less than with a battery freshly charged. This loss is due to local chemical actions taking place inside the batteries.

Thirdly, the batteries rapidly wear out, and after a few months' work require new lead plates.

Fourthly, their first cost per unit of electrical energy which they can store (in the form of chemical energy) is very heavy.

There is no doubt that the interest and depreciation on a set of secondary batteries large enough to enable an electric light plant to work day and night, and so give out to the lamps no electricity in the day but a double quantity in the night, is vastly greater than the interest and depreciation on a complete duplicate set of engines, boilers, and dynamos.

The more we consider the question of the storage of electrical energy, the more we shall be convinced that the best form of potential energy in which to keep it is in that of the potential energy of coals and compressed steam, and the proper place in which to store it is a spare boiler kept ready to actuate a spare engine and dynamo.

The potential energy contained in a battery rapidly leaks out. Boilers do not leak at all. Engines are comparatively cheap, and last indefinitely; batteries are dear, and wear out rapidly. The only storage apparatus which is worthy the name is a spare boiler full of steam, with a banked fire, and a spare engine and dynamo, kept warm, well oiled, and ready to start at a moment's notice.

Storage of High-pressure Currents.

There is one form in which the proposed use of secondary batteries will deserve consideration when a practical secon-

dary battery shall have been constructed. It has been proposed that the engines and dynamos shall be placed outside the town to be lighted, and that the batteries shall be kept in the centre of the town. It is then proposed that a high-pressure current shall be brought from the dynamos to the batteries by the use of fine wire, a great number of the batteries being arranged "in series" to receive the charge, and then altered to a "quantity" arrangement to discharge to the lamps.

The relative economic advantages of this, and of a direct supply, may be calculated by the method given in the last chapter as applied to the Goulard and Gibbs system.

CHAPTER XVII.

EXPERIMENTAL MEASUREMENTS OF HORSE-POWER.

THE horse-power being developed at any moment by each cylinder of an engine is given by the formula—

$$H.P. = \frac{2SRAP}{33,000} \quad . \quad . \quad . \quad . \qquad (60)$$

where—

> S = Length of stroke in feet.
> R = Number of revolutions per minute.
> A = Area of piston in square inches.
> P = Mean pressure on the piston during the whole stroke in pounds per square inch.

It will be noted on examining this formula that 2SR is the speed in feet per minute at which the piston moves; and AP is the mean total weight in pounds pressing on the piston.

2SRAP is therefore the number of foot-pounds per minute which is being expended.

One H.P. is equal to 33,000 foot-pounds per minute, and hence the number of H.P. is equal to the number of foot-pounds per minute divided by 33,000, which gives the formula (60) above.

For any given engine the quantities S and A are constant, R is kept constant by the governor, and P constantly varies, for as the load is changed, as for instance, by the turning on or shutting off of lamps, the throttle valve (or expansion valve, as the case may be) is more or less opened or shut by the action of the governor. When the valve is more nearly closed, P of course diminishes.

All *indicators* are instruments for measuring P (the mean pressure in the cylinder) at any instant.

RICHARDS' INDICATOR.

Richards' indicator (Fig. 91) is an instrument of this de-

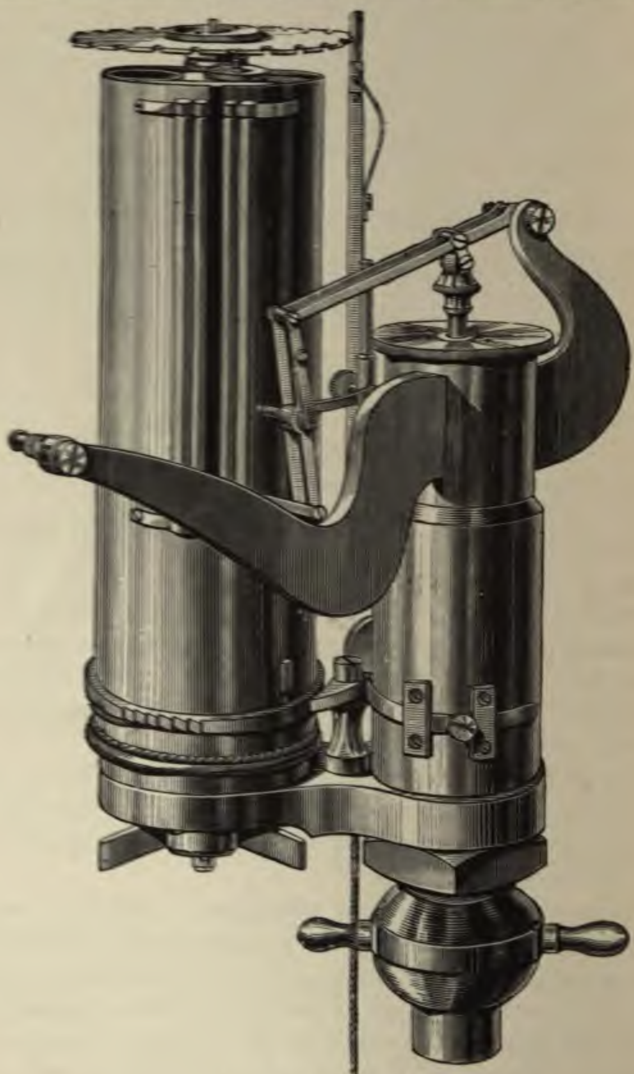


Fig. 91.

scription. It consists of a small steam cylinder with a piston in it. The cylinder is connected by a pipe to the cylinder

of the engine, and is driven up by the steam against a spring which tends to force it down. The height at which the small piston stands at any instant, indicates the pressure in the engine-cylinder at that instant. This pressure varies from zero at one part of the stroke to its maximum value at another part. In order to obtain its *mean value* during the whole stroke, a pencil is attached to the rod of the indicator-piston, which, as the piston moves, would draw a vertical line on a stationary piece of paper. The maximum height of this line would represent the maximum steam pressure during the stroke. The paper is, however, not stationary, but is wound round a barrel which is connected by a string to the piston-rod of the engine so that it revolves backwards and forwards on its axis, making about three-quarters of a revolution for each stroke. If the indicator-piston is at rest, the pencil will trace on the paper a horizontal line round the barrel. When the indicator-piston and paper both move, a curved line will be traced by the pencil, whose vertical height above any point of the horizontal zero line gives the pressure in the cylinder at the portion of the stroke represented by that point.

The total area of the space included between the curve and the horizontal line, divided by the length of the horizontal line, gives the mean pressure throughout the stroke, and this is the quantity P which we want to know.

I do not propose to give any directions for the practical use of the indicator, as it is well understood by engineers, and whenever an engine is erected, there will always be some one in charge who will know how to indicate it.

Boys' Engine-power Meter.

Mr. Vernon Boys has devised an instrument for indicating the mean pressure in an engine-cylinder, which consists of a cylinder, piston, and spring, the communication with which from the engine-cylinder is made by a long, fine pipe, through which the steam cannot move rapidly. Instead of oscillating up and down during the stroke, the friction of the steam causes the piston to remain stationary in the position indicating the mean pressure. I have had no practical ex-

perience of this instrument, but it may probably be very useful as a continuous indicator for the engines of a central station. It can also be made self-recording.

MAXIMUM HORSE-POWER.

The maximum value of P, the mean pressure which an engine working at a fairly economical expension rate can have, may be taken as at about half the boiler pressure, and therefore if we wish to find the maximum horse-power which we are likely to get out of a given engine, we may use the formula (60), and take P as half the boiler pressure.

All the above calculations apply to simple engines with one cylinder. When two cylinders are used, the horse-power will of course be doubled. The method of obtaining the H.P. of compound engines is more complex, and I shall not touch upon it.

HORSE-POWER GIVEN OFF BY A SHAFT.

With small experimental machines it is convenient some-

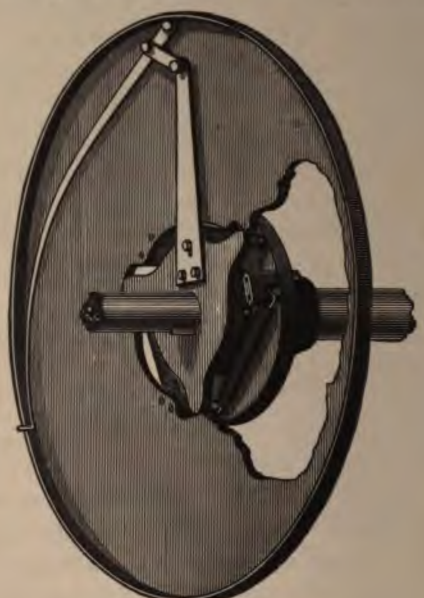


Fig. 92.

times to measure the horse-power which is being transmitted

by a shaft or coupling. Fig. 92 represents an apparatus for that purpose devised by Professor Ayrton. The coupling between the driving and receiving shaft is not rigid, but is made by a spring. The receiving shaft therefore lags behind the other by an amount depending on the force applied to it. This lagging causes the white lever to move in towards the shaft, and the circle described by the bright bead at its end is diminished in diameter. The diameter of this circle gives the pounds of pull. The velocity of the shaft gives the feet per minute, and the product of the two is the foot-pounds per minute, or 33,000 times the horse-power.

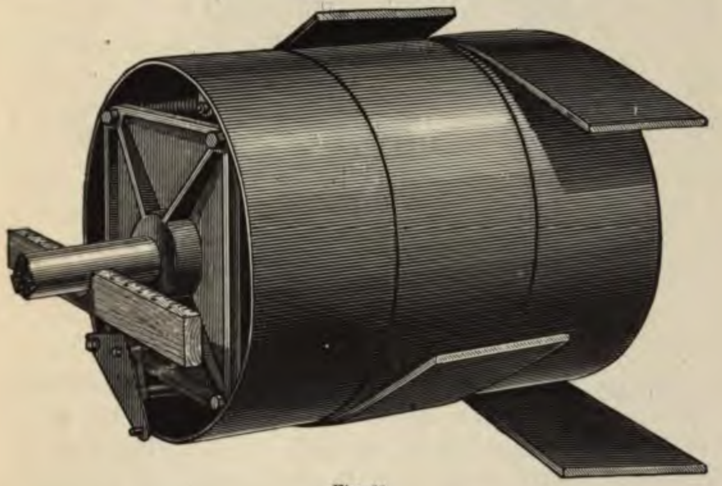


Fig. 93.

Fig. 93 is another form of the same apparatus arranged for measuring the H.P. transmitted by a belt.

Speed.

Young's Speed Indicator.

Fig. 94 represents an apparatus by which the speed of any shaft, of which the end is accessible, can be at once noted without timing. On the little point being pressed into the hollow at the end of the shaft, the hand at once points to the number of revolutions per minute.

The apparatus consists of a miniature governor like an engine-governor, but controlled by a spring instead of by a weight. As the balls fly out they move a lever, which moves the hand.

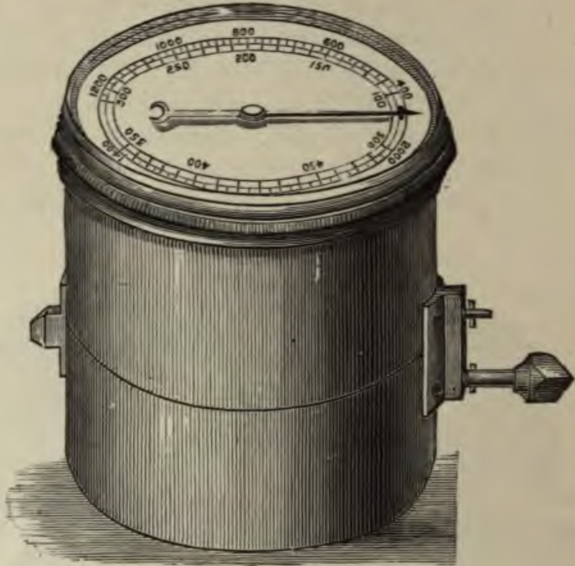


Fig. 94.

The point can be put on either of the two spindles shown, one being used for speeds under 500 revolutions per minute, and indicating on the inner circle on the dial, and the other for speeds up to 2000 revolutions, and indicating on the outer circle.

CHAPTER XVIII.

PHOTOMETRY.

It is very important to be able to measure accurately the candle-power of incandescent lamps.

The simplest photometer known is one of the best in practice.

It consists of a rod or wire placed about $1\frac{1}{2}$ inches in front of a white screen. The two lights which are to be compared, as for instance, an incandescent lamp and a standard candle, are placed at different distances from the screen, and the distance of one varied until the two shadows of the wire thrown on the screen are of equal tint.

The relative intensities of the lights are then inversely as the squares of their distances from the screen.

In practice, the electric lamp is placed at a fixed distance of say 100 inches from the screen, and the candle is shifted till the shadows are equal. Then if D_L is the distance of the lamp from the screen, and D_C that of the candle, the candle-power K is—

$$K = \left(\frac{D_L}{D_C}\right)^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (61)$$

To save working out this equation for every experiment, the distances D_C of the candle corresponding to different candle-powers K are worked out by the following formula,—

$$D_C = \frac{D_L}{\sqrt{K}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (62)$$

They are then marked on the board, and their corresponding

candle-powers marked on them. To take an observation, the candle is then slid along till the shadows are equal, and the candle-power read off from the position of the candle on the board.

"Standard candles" can be obtained of Messrs. Sugg, at Charing Cross.

This firm also make a very elaborate photometer, which they supply to gas-works, and which is suitable to large electric-light factories. It is unnecessary to occupy space by describing it here, as the details of it are only of interest to those who have to use it, and they will be understood from the directions sent with it.

CHAPTER XIX.

CENTRAL STATION LIGHTING.

I HAD intended to write a long chapter with the above heading, but, for various reasons, I am not yet prepared to do so. I have, however, left in the heading for the convenience of inserting such a chapter in a future edition of this book, should one ever be required.

CHAPTER XX.

METERS.

There have been a great number of patents taken out for electric-meters, i.e. for instruments to continuously register the number of commercial units of electric energy used by each consumer.

None of them, however, as yet work satisfactorily. There is no doubt that good meters will be forthcoming when wanted, i.e. when district lighting under this year's Provisional Orders is commenced next year. At present there has been no demand for them, and inventors have been busy at other things.

The three principal types of meter now in existence in a crude form are Edison's, Hopkinson's, and my own.

Edison's consists of two plates of copper in an electrolytic cell, through which a small known fraction of the current passes. The total energy consumed is then measured by weighing the plates, and noting the respective loss and gain from month to month.

Hopkinson's meter consists of a small electric motor, which revolves at varying speed according to the strength of current, and which records the total number of revolutions taken per month.

My own meter consists of some kind of galvanometer, carrying an eccentric or "snail" wheel, so arranged that the vertical radius gets less as the current gets stronger. At short intervals an arm, lifted by clockwork, drops from a fixed zero position to the edge of the snail. The distance through which it moves is greater as the current is greater. The apparatus records the total length of all the journeys taken by the arm in a month or quarter, in its searches for the galvanometer-wheel.

CHAPTER XXI.

FIRE RISKS.

THE risk of fire from electric light apparatus is very small, but fires may occur through the carelessness or ignorance of the engineers who erect the plant. In order to minimize this risk, the Society of Telegraph Engineers have drawn up the following regulations :—

RULES AND REGULATIONS

FOR THE PREVENTION OF FIRE RISKS ARISING FROM ELECTRIC LIGHTING,

Recommended by the Council of the Society of Telegraph Engineers and of Electricians, in accordance with the Report of the Committee appointed by them on May 11, 1882, to consider the subject.

MEMBERS OF THE COMMITTEE.

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These rules and regulations are drawn up for the reduction to a minimum, in the case of electric lighting, of those risks of fire which are inherent in every system of artificial illumination, and also for the guidance and instruction of those who have, or who contemplate having, electric lighting apparatus installed in their premises.

The difficulties that beset the electrical engineer are chiefly internal and invisible, and they can only be effectually guarded against by "testing," or probing with electric currents. They depend chiefly on leakage, undue resistance in the conductor, and bad joints, which lead to waste of energy and the dangerous production of heat. These defects can only be detected by measuring, by means of special apparatus, the currents that are either ordinarily or for the purpose of testing, passed through the circuit. Should wires become perceptibly warmed by the ordinary current, it is an indication that they are too small for the work they have to do, and that they should be replaced by larger wires. Bare or exposed conductors should always be within visual inspection, and as far out of reach as possible, since the accidental falling on to, or the thoughtless placing of other conducting bodies upon such conductors would lead to "short circuiting," and the consequent sudden generation of heat due to an increased current in conductors not adapted to carry it with safety.

The necessity cannot be too strongly urged for guarding against the presence of moisture and the use of "earth" as part of the circuit. Moisture leads to loss of current and to the destruction of the conductor by electrolytic corrosion, and the injudicious use of "earth" as a part of the circuit tends to magnify every other source of difficulty and danger.

The chief dangers of every new application of electricity arise from ignorance and inexperience on the part of those who supply and fit up the requisite plant.

The greatest element of safety is therefore the employment of skilled and experienced electricians to supervise the work.

I. The Dynamo Machine.

1. The dynamo machine should be fixed in a dry place.

2. It should not be exposed to dust or flyings.

3. It should be kept perfectly clean and its bearings well oiled.

4. The insulation of its coils and conductors should be practically perfect.

5. All conductors in the dynamo-room should be firmly supported, well insulated, conveniently arranged for inspection, and marked or numbered.

II. The Wires.

6. Every switch or commutator used for turning the current on or off should be constructed so that when it is moved and left it cannot permit of a permanent arc or of heating.

7. Every part of the circuit should be so determined, that the gauge of wire to be used is properly proportioned to the currents it will have to carry, and all junctions with a smaller conductor should be fitted with a suitable safety fuse or protector, so that no portion of the conductor should ever be allowed to attain a temperature exceeding 150° F.

8. Under ordinary circumstances complete metallic circuits should be used; the employment of gas or water pipes as conductors for the purpose of completing the circuit, should not in any case be allowed.

9. Bare wires passing over the tops of houses should never be less than seven feet clear of any part of the roof, and all wires crossing thoroughfares should invariably be high enough to allow fire escapes to pass under them.

10. It is most essential that joints should be electrically and mechanically perfect and united by solder.

11. The position of wires when underground should be clearly indicated, and they should be laid down so as to be easily inspected and repaired.

12. All wires used for indoor purposes should be efficiently insulated, either by being covered throughout with some insulating medium, or, if bare, by resting on insulated supports.

13. When these wires pass through roofs, floors, walls, or partitions, or where they cross or are liable to touch metallic masses, like iron girders or pipes, they should be thoroughly protected by suitable additional covering; and where they are liable to abrasion from any cause, or to the depredations of rats or mice, they should be efficiently encased in some hard material.

14. Where indoor wires are put out of sight, as beneath flooring, they should be thoroughly protected from mechanical injury, and their position should be indicated.

N.B.—The value of frequently testing the apparatus and circuits cannot be too strongly urged. The escape of electricity cannot be detected by the sense of smell, as can gas, but it can be detected by apparatus far more certain and delicate. Leakage not only means waste, but in the presence of moisture it means destruction of the conductor and its insulating covering, by electrolytic action.

III. Lamps.

15. Arc lamps should always be guarded by proper lanterns to prevent danger from falling incandescent pieces of carbon, and from ascending sparks. Their globes should be protected with wire netting.

16. The lanterns, and all parts which are to be handled, should be insulated from the circuit.

The "safety-fuse" spoken of in § 7 consists of a short length of wire of lead or other fusible metal inserted in the circuit, the diameter being such that, if the current increases say 50 per cent. above its proper value, the fusible wire will melt and break the circuit.

	·026	·6601	·00053093	·342535	10·789	·098082	3·0409	163·13	328·85	83·153	·047246	·051669	21·165	19·354
	·027	·6358	·00057255	·369390	11·635	·10577	3·2793	151·27	304·94	77·108	·043812	·047914	22·824	20·871
22s	·028	·7112	·00061575	·397259	12·513	·11375	3·5268	140·65	283·54	71·698	·040738	·044552	24·546	22·446
	·029	·7366	·00066052	·426142	13·422	·11202	3·7830	131·13	264·34	66·839	·037976	·041531	26·331	24·078
	·030	·7620	·00070686	·456038	14·364	·13058	4·0485	122·53	247·00	62·457	·035485	·038807	28·180	25·769
	·031	·7874	·00075477	·486947	15·338	·13944	4·3230	114·75	231·32	58·493	·033235	·036346	30·088	27·513
21s	·032	·8128	·00080425	·518870	16·343	·14857	4·6063	107·70	217·09	54·894	·031190	·034110	32·061	29·317
	·033	·8382	·00085531	·551809	17·381	·15801	4·8988	101·46	204·54	51·618	·029329	·032075	34·095	31·177
	·034	·8636	·00090792	·585755	18·450	·16773	5·2001	95·392	192·30	48·626	·027626	·030212	36·196	33·099
	·035	·8890	·00096211	·620718	19·551	·17774	5·5105	90·020	181·47	45·887	·026071	·028512	38·355	35·073
20s	·036	·9144	·00101788	·656694	20·684	·18804	5·8298	85·089	171·53	43·373	·024642	·026949	40·580	37·107
	·037	·9398	·00107521	·693684	21·849	·19863	6·1581	80·550	162·38	41·060	·023328	·025512	42·865	39·197
	·038	·9652	·00113412	·731687	23·046	·20951	6·4955	76·368	153·95	38·928	·022118	·024189	45·210	41·341
	·039	·9906	·00119459	·770704	24·275	·22068	6·8419	72·504	146·16	36·957	·020999	·022965	47·620	43·545
	·040	1·0160	·00125664	·810734	25·536	·23215	7·1973	68·922	138·94	35·132	·019962	·021831	50·093	45·806
	·041	1·0414	·00132026	·851777	26·829	·24390	7·5618	65·599	132·24	33·439	·019001	·020780	52·627	48·123
19s	·042	1·0668	·00138545	·893834	28·153	·25594	7·9349	62·513	126·02	31·866	·018104	·019799	55·235	50·508
	·043	1·0922	·00145220	·936904	29·510	·26827	8·3174	59·636	120·22	30·401	·017273	·018890	57·892	52·938
	·044	1·1176	·00152053	·980988	30·899	·28090	8·7089	56·953	114·82	29·035	·016495	·018039	60·623	55·435
	·045	1·1430	·00159043	1·02608	32·319	·29381	9·1091	54·457	109·78	27·759	·015772	·017249	63·400	57·974
	·046	1·1684	·00166191	1·07220	33·771	·30701	9·5184	52·116	105·06	26·566	·015095	·016508	66·245	60·576
	·047	1·1938	·00173495	1·11932	35·256	·32051	9·9369	49·918	100·63	25·447	·014458	·015812	69·162	63·243
	·048	1·2192	·00180956	1·16745	36·772	·33429	10·364	47·864	96·488	24·397	·013864	·015162	72·127	65·954
18s	·049	1·2446	·00188575	1·21661	38·320	·34836	10·800	45·931	92·592	23·412	·013302	·014547	75·177	68·743
	·050	1·2700	·00196350	1·26677	39·900	·36273	11·246	44·110	88·920	22·485	·012776	·013972	78·271	71·572
	·051	1·2954	·00204283	1·31795	41·512	·37738	11·700	42·398	85·470	21·612	·012280	·013430	81·430	74·461
	·052	1·3208	·00212372	1·37014	43·156	·39233	12·164	40·781	82·210	20·788	·011812	·012918	84·656	77·411
	·053	1·3462	·00220619	1·42334	44·832	·40756	12·636	39·258	79·139	20·011	·011369	·012433	87·959	80·431
	·054	1·3716	·00229023	1·47756	46·539	·42308	13·117	37·818	76·237	19·277	·010951	·011976	91·315	83·500
	·055	1·3970	·00237883	1·53279	48·279	·43890	13·607	36·456	73·492	18·582	·010559	·011548	94·700	86·595
	·056	1·4224	·00246301	1·58904	50·051	·45501	14·107	35·164	70·887	17·925	·010184	·011137	98·195	89·791
	·057	1·4478	·00255176	1·64629	51·854	·47140	14·615	33·942	68·423	17·301	·0098316	·010752	101·711	93·006
17s	·058	1·4732	·00264209	1·70457	53·689	·48808	15·132	32·782	66·085	16·710	·0094932	·010382	105·366	96·321
	·059	1·4986	·00273398	1·76385	55·557	·50506	15·659	31·679	63·861	16·148	·0091764	·010035	108·978	99·651
	·060	1·5240	·00282744	1·82415	57·456	·52233	16·194	30·632	61·751	15·614	·0088704	·0097008	112·728	103·08
	·061	1·5494	·00292247	1·885461	59·387	·53988	16·738	29·636	59·744	15·107	·0085824	·0093857	116·518	106·545
	·062	1·5748	·00301908	1·947790	61·350	·55773	17·291	28·688	57·832	14·623	·0083088	·0090865	120·354	110·053
	·063	1·6002	·00311725	2·011125	63·345	·57586	17·854	27·785	56·011	14·163	·0080460	·0087991	124·285	113·648

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Diameter		Section		Weight per length.			Length per weight.		Resistance of Pure Copper at 75° F.				
										Ohms per length.			Length per Ohm.	
Nearest B.W. Gauge.	in Inches.	in Milli-metres.	in Square Inches.	in Square Millimetres.	lbs. per 1760 yds.	ounces per yard.	grammes per metre or kilo-grammes per kilo-metre.	Yards per pound.	Metres per kilo-gramme.	Ohms per 1760 yds.	Ohms per yard.	Ohms per metre.	Yards.	Metres.
	·064	1·6256	·00321700	2·075480	65·372	·59429	18·425	26·923	54·274	13·723	·0077976	·0085278	128·240	117·264
16s	·065	1·6510	·00331832	2·140847	67·431	·61301	19·005	26·101	52·617	13·305	·0075600	·0082676	132·275	120·954
	·066	1·6764	·00342120	2·207221	69·522	·63202	19·595	25·315	51·033	12·904	·0073332	·0080196	136·365	124·694
	·067	1·7018	·00352566	2·274615	71·644	·65131	20·193	24·566	49·522	12·522	·0071136	·0077794	140·576	128·544
15½s	·068	1·7272	·00363169	2·343021	73·799	·67090	20·800	23·849	48·077	12·156	·0069084	·0075550	144·752	132·363
	·069	1·7526	·00373929	2·412440	75·986	·69078	21·417	23·162	46·692	11·807	·0067068	·0073346	149·101	136·340
	·070	1·7780	·00384846	2·482872	78·204	·71094	22·042	22·502	45·368	11·472	·0065196	·0071296	153·388	140·260
	·071	1·8034	·00395920	2·554317	80·454	·73140	22·676	21·876	44·099	11·151	·0063360	·0069291	157·827	144·319
15s	·072	1·8288	·00407151	2·62678	82·737	·75215	23·319	21·273	42·883	10·843	·0061596	·0067361	162·348	148·453
	·073	1·8542	·00418539	2·70025	85·051	·77319	23·972	20·693	41·715	10·548	·0059940	·0065550	166·834	152·555
	·074	1·8796	·00430085	2·77474	87·397	·79452	24·633	20·138	40·596	10·265	·0058320	·0063779	171·467	156·791
	·075	1·9050	·00441788	2·85024	89·775	·81614	25·303	19·605	39·521	9·9931	·0056772	·0062086	176·143	161·067
	·076	1·9304	·00453647	2·92675	92·185	·83805	25·982	19·092	38·488	9·7319	·0055296	·0060471	180·846	165·368
14½s	·077	1·9558	·00465663	3·004271	94·627	·86025	26·671	18·599	37·494	9·4808	·0053856	·0058897	185·680	169·788
	·078	1·9812	·00477837	3·082813	97·101	·88274	27·368	18·125	36·539	9·2392	·0052488	·0057401	190·517	174·211
	·079	2·0066	·00490168	3·162368	99·606	·90551	28·074	17·670	35·620	9·0068	·0051156	·0055944	195·481	178·750
	·080	2·0320	·00502656	3·242935	102·15	·92863	28·790	17·230	34·734	8·7830	·0049896	·0054566	200·417	183·264
	·081	2·0574	·00515301	3·324516	104·71	·95191	29·513	16·808	33·883	8·5675	·0048672	·0053228	205·456	187·871
	·082	2·0828	·00528103	3·407109	107·32	·97564	30·248	16·380	33·020	8·3598	·0047484	·0051928	210·599	192·574
14s	·083	2·1082	·00541062	3·490716	109·95	·99954	30·989	15·907	32·269	8·1596	·0046368	·0050708	215·667	197·208
	·084	2·1336	·00554178	3·575335	112·61	1·0237	31·739	15·629	31·507	7·9665	·0045252	·0049488	220·983	202·069
	·085	2·1590	·00567452	3·660973	115·31	1·0483	32·500	15·263	30·769	7·7801	·0044208	·0048346	226·202	206·842
	·086	2·1844	·00580882	3·747618	118·04	1·0731	33·270	14·910	30·057	7·6003	·0043164	·0047204	231·675	211·846
	·087	2·2098	·00594469	3·835276	120·80	1·0982	34·047	14·630	29·371	7·4265	·0042192	·0046141	237·013	216·727
	·088	2·2352	·00608213	3·923947	123·60	1·1236	34·837	14·239	28·705	7·2587	·0041256	·0045118	242·387	221·641

13½s	·089	2·2606	·00622115	4·013637	126·42	1·1493	35·631	13·922	28·065	7·0965	·0040620	·0044094	248·015	226·788
	·090	2·2830	·00636174	4·104338	129·28	1·1753	36·438	13·614	27·444	6·9397	·0039420	·0043110	253·677	231·965
	·091	2·3144	·00650390	4·196056	132·16	1·2015	37·249	13·387	26·846	6·7880	·0038556	·0042165	259·363	237·164
	·092	2·3368	·00664763	4·288785	135·09	1·2281	38·075	13·029	26·264	6·6412	·0037728	·0041259	265·057	242·371
	·093	2·3622	·00679292	4·382520	138·04	1·2549	38·907	12·750	25·702	6·4992	·0036936	·0040393	270·740	247·568
	·094	2·3876	·00693979	4·477275	141·02	1·2820	39·746	12·480	25·160	6·3616	·0036144	·0039527	276·672	252·992
13s	·095	2·4130	·00708824	4·573049	144·04	1·3095	40·598	12·219	24·632	6·2284	·0035388	·0038700	282·584	258·398
	·096	2·4384	·00723825	4·669829	147·09	1·3372	41·457	11·965	24·121	6·0993	·0034657	·0037901	288·541	263·845
	·097	2·4638	·00738983	4·767623	150·17	1·3652	42·325	11·630	23·627	5·9742	·0033944	·0037121	294·604	269·389
	·098	2·4892	·00754298	4·866427	153·28	1·3935	43·202	11·482	23·147	5·8529	·0033257	·0036370	300·687	274·952
	·099	2·5146	·00769771	4·966254	156·42	1·4220	44·087	11·251	22·682	5·7353	·0032587	·0035637	306·872	280·607
	·100	2·5400	·00785400	5·067087	159·60	1·4509	44·983	11·027	22·230	5·6211	·0031939	·0034929	313·092	286·295
	·101	2·5654	·00801187	5·168938	162·81	1·4801	45·888	10·810	21·792	5·5104	·0031309	·0034240	319·392	292·056
12½s	·102	2·5908	·00817130	5·271796	166·05	1·5095	46·801	10·599	21·367	5·4029	·0030697	·0033570	325·767	297·885
	·103	2·6162	·00833231	5·375673	169·32	1·5393	47·723	10·394	20·954	5·2985	·0030103	·0032921	332·189	303·757
	·104	2·6416	·00849489	5·480563	172·62	1·5693	48·653	10·196	20·554	5·1971	·0029527	·0032291	338·670	309·684
	·105	2·6670	·00865904	5·586466	175·96	1·5996	49·594	10·002	20·164	5·0985	·0028969	·0031681	345·190	315·646
	·106	2·6924	·00882475	5·693376	179·33	1·6303	50·544	9·8140	19·784	5·0028	·0028426	·0031087	351·787	321·678
	·107	2·7178	·00899204	5·801305	182·73	1·6612	51·502	9·6319	19·417	4·9097	·0027896	·0030507	358·476	327·794
	·108	2·7432	·00916091	5·910253	186·16	1·6924	52·469	9·4544	19·059	4·8192	·0027382	·0029945	365·203	333·946
12s	·109	2·7686	·00933134	6·020207	189·62	1·7238	53·444	9·2816	18·711	4·7312	·0026881	·0029397	372·011	340·171
	·110	2·7940	·00950334	6·131174	193·12	1·7556	54·431	9·1136	18·372	4·6456	·0026395	·0028866	378·855	346·429
	·111	2·8194	·00967691	6·243154	196·64	1·7897	55·423	8·9504	18·043	4·5622	·0025924	·0028350	385·750	352·734
	·112	2·8448	·00985206	6·356155	200·20	1·8200	56·426	8·7912	17·722	4·4811	·0025463	·0027846	392·731	359·118
	·113	2·8702	·01002877	6·470161	203·79	1·8526	57·438	8·6364	17·410	4·4022	·0025013	·0027354	399·795	365·577
11½s	·114	2·8956	·01020706	6·585186	207·42	1·8856	58·461	8·4851	17·105	4·3253	·0024574	·0026874	406·935	372·106
	·115	2·9210	·01038692	6·701225	211·07	1·9188	59·490	8·3383	16·809	4·2504	·0024149	·0026409	414·101	378·659
	·116	2·9464	·01056834	6·818270	214·76	1·9524	60·530	8·1954	16·521	4·1774	·0023735	·0025957	421·313	385·253
	·117	2·9718	·01075134	6·936335	218·48	1·9862	61·579	8·0555	16·239	4·1063	·0023332	·0025516	428·594	391·911
	·118	2·9972	·01093591	7·055412	222·23	2·0203	62·636	7·9196	15·965	4·0370	·0022939	·0025086	435·940	398·628
	·119	3·0226	·01112205	7·175502	226·01	2·0546	63·700	7·7876	15·699	3·9695	·0022554	·0024665	443·380	405·432
11s	·120	3·0480	·01130976	7·296605	229·82	2·0893	64·775	7·6582	15·438	3·9036	·0022180	·0024256	450·857	412·269
	·121	3·0734	·01149904	7·418721	233·67	2·1243	65·860	7·532	15·184	3·8393	·0021812	·0023854	458·456	419·217
	·122	3·0988	·01168989	7·541849	237·55	2·1595	66·954	7·4092	14·936	3·7766	·0021460	·0023469	465·976	426·094
	·123	3·1242	·01188232	7·665998	241·46	2·1951	68·056	7·2891	14·694	3·7155	·0021110	·0023086	473·707	433·163
	·124	3·1496	·01207631	7·791152	245·40	2·2309	69·166	7·1720	14·458	3·6558	·0020772	·0022716	481·422	440·218
	·125	3·1750	·01227188	7·917326	249·37	2·2670	70·285	7·0579	14·228	3·5975	·0020441	·0022354	489·219	447·347
	·126	3·2004	·01246901	8·044507	253·38	2·3035	71·415	6·9463	14·003	3·5407	·0020117	·0022000	497·090	454·545

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI
[illegible]	In inches	In millimetres	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10½	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	·137	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	·138	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	·139	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	·140	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9½	·141	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	·142	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	·143	3·6322	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	·144	3·6576	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	·145	3·6830	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	·146	3·7084	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	·147	3·7338	[illegible]	[illegible]	[illegible]	8·1353	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9	·148	3·7592	[illegible]	[illegible]	[illegible]	8·1781	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	·149	3·7846	[illegible]	[illegible]	[illegible]	8·2212	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	·150	3·8100	·01707150	11·400045	350·10	8·2645	101·213	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	·151	3·8354	[illegible]	11·553407	303·90	8·3082	102·565	4·8305	0·7100	2·1068	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

	·152	3·8608	·01814588	11·706996	368·74	3·3522	103·929	4·7731	9·6220	2·4330	·0013824	·0015117	723·424	661·507
	·153	3·8862	·01838543	11·861544	373·61	3·3965	105·302	4·7108	9·4965	2·4013	·0013644	·0014921	732·926	670·196
	·154	3·9116	·01862655	12·017105	378·51	3·4410	106·683	4·6498	9·3735	2·3702	·0013468	·0014729	742·481	678·933
	·155	3·9370	·01886924	12·173679	383·44	3·4858	108·073	4·5900	9·2530	2·3397	·0013295	·0014539	752·184	687·805
3½s	·156	3·9624	·01911349	12·331259	388·40	3·5309	109·471	4·5314	9·1348	2·3098	·0013126	·0014354	761·877	696·669
	·157	3·9878	·01935933	12·489865	393·40	3·5764	110·880	4·4734	9·0178	2·2805	·0012956	·0014168	771·880	705·816
	·158	4·0132	·01960673	12·649478	398·43	3·6221	112·298	4·4174	8·9049	2·2517	·0012794	·0013991	781·645	714·745
	·159	4·0386	·01985570	12·810103	403·48	3·6680	113·721	4·3621	8·7934	2·2235	·0012632	·0013814	791·660	723·903
	·160	4·0640	·02010624	12·971742	408·58	3·7144	115·158	4·3076	8·6837	2·1958	·0012478	·0013645	801·466	732·869
	·161	4·0894	·02035835	13·134393	413·70	3·7609	116·601	4·2543	8·5762	2·1686	·0012323	·0013476	811·517	742·060
	·162	4·1148	·02061204	13·298064	418·85	3·8077	118·053	4·2020	8·4708	2·1419	·0012168	·0013307	821·823	751·484
	·163	4·1402	·02086639	13·462160	424·04	3·8549	119·516	4·1506	8·3671	2·1157	·0012020	·0013145	831·952	760·746
	·164	4·1656	·02112412	13·628437	429·26	3·9023	120·987	4·1001	8·2654	2·0900	·0011876	·0012988	842·007	769·941
8s	·165	4·1910	·02138252	13·795147	434·51	3·9501	122·467	4·0506	8·1655	2·0647	·0011732	·0012830	852·377	779·423
	·166	4·2164	·02164248	13·962862	439·79	3·9981	123·955	4·0019	8·0674	2·0399	·0011588	·0012673	862·937	789·079
	·167	4·2418	·02190402	14·131598	445·11	4·0465	125·454	3·9382	7·9389	2·0155	·0011452	·0012524	873·204	798·467
	·168	4·2672	·02216713	14·301346	450·46	4·0951	126·962	3·9072	7·8764	1·9916	·0011315	·0012374	883·788	808·146
	·169	4·2926	·02243181	14·472107	455·83	4·1439	128·476	3·8611	7·7836	1·9681	·0011182	·0012229	894·267	817·728
	·170	4·3180	·02269806	14·643880	461·24	4·1931	130·000	3·8158	7·6923	1·9450	·0011052	·0012086	904·849	827·404
	·171	4·3434	·02296588	14·816667	466·69	4·2426	131·537	3·7712	7·6024	1·9224	·0010922	·0011945	915·529	837·170
7½s	·172	4·3688	·02323527	14·990467	472·16	4·2924	133·078	3·7275	7·5143	1·9001	·0010796	·0011807	926·230	846·955
	·173	4·3942	·02350624	15·165286	477·67	4·3425	134·631	3·6846	7·4277	1·8782	·0010670	·0011669	937·183	856·971
	·174	4·4196	·02377877	15·341111	483·20	4·3927	136·190	3·6424	7·3427	1·8566	·0010548	·0011535	948·071	866·927
	·175	4·4450	·02405288	15·517956	488·77	4·4434	137·760	3·6009	7·2590	1·8355	·0010429	·0011405	958·877	876·808
	·176	4·4704	·02432855	15·695807	494·38	4·4944	139·341	3·5600	7·1766	1·8147	·0010310	·0011275	969·932	886·917
	·177	4·4958	·02460580	15·874678	500·01	4·5455	140·928	3·5199	7·0958	1·7942	·0010195	·0011149	980·895	896·941
	·178	4·5212	·02488461	16·054555	505·68	4·5971	142·526	3·4806	7·0162	1·7741	·0010080	·0011023	992·107	907·194
	·179	4·5466	·02516500	16·235451	511·37	4·6488	144·130	3·4418	6·9382	1·7544	·0009968	·0010902	1003·118	917·262
7s	·180	4·5720	·02544696	16·417361	517·10	4·7009	145·845	3·4012	6·8565	1·7349	·0009857	·0010780	1014·472	927·644
	·181	4·5974	·02573049	16·600283	522·87	4·7534	147·3709	3·36606	6·78560	1·7158	·0009749	·0010662	1025·698	937·910
	·182	4·6228	·02601559	16·784218	528·66	4·8060	149·0028	3·32920	6·71128	1·6970	·0009641	·0010544	1037·178	948·407
	·183	4·6482	·02630226	16·969166	534·48	4·8589	150·6432	3·29295	6·63820	1·6785	·0009536	·0010429	1048·615	958·865
	·184	4·6736	·02659050	17·155127	540·34	4·9122	152·2948	3·25723	6·56621	1·6603	·0009432	·0010315	1060·204	969·462
	·185	4·6990	·02688032	17·342107	546·23	4·9657	153·9549	3·22215	6·49548	1·6424	·0009331	·0010204	1071·737	980·008
	·186	4·7244	·02717170	17·530094	552·15	5·0195	155·6235	3·18756	6·42576	1·6248	·0009230	·0010094	1083·415	990·687
	·187	4·7498	·02746165	17·719094	558·11	5·0739	157·3033	3·15353	6·35715	1·6075	·0009133	·0009988	1094·913	1001·201
	·188	4·7752	·02775918	17·909113	564·09	5·1281	158·9888	3·12009	6·28975	1·5904	·0009036	·0009882	1106·659	1011·941
	·189	4·8006	·02805527	18·100138	570·11	5·1828	160·6855	3·08715	6·22333	1·5736	·0008942	·0009779	1118·314	1022·599

Nearest B.W. Gauge.	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Diameter		Section		Weight per length.			Length per weight.		Resistance of Pure Copper at 75° F.				
										Ohms per length.			Length per Ohm.	
	In Inches.	In Milli-Metres.	In Square Inches.	In Square Millimetres.	lbs. per 1760 yds.	ounces per yard.	grammes per metre or kilo-grammes per kilo-metre.	Yards per pound.	Metres per kilo-gramme.	Ohms per 1760 yds.	Ohms per yard.	Ohms per metre.	Yards.	Metres.
	·190	4·8260	·02835294	18·292189	576·16	5·2378	162·3907	3·05479	6·15799	1·5571	·0008849	·0009677	1130·102	1033·378
6½*	·191	4·8514	·02865218	18·485241	582·24	5·2931	164·1049	3·02269	6·09508	1·5408	·0008755	·0009575	1142·140	1044·386
	·192	4·8768	·02895299	18·679311	588·35	5·3486	165·8404	2·99144	6·03040	1·5248	·0008665	·0009476	1154·074	1055·298
	·193	4·9022	·02925537	18·874395	594·40	5·4046	167·5670	2·96065	5·96812	1·5091	·0008575	·0009378	1166·133	1066·325
	·194	4·9276	·02955931	19·070485	600·67	5·4606	169·3088	2·93009	5·90672	1·4936	·0008485	·0009279	1178·575	1077·702
	·195	4·9530	·02986484	19·267600	606·88	5·5171	171·0491	2·90010	5·84627	1·4783	·0008399	·0009185	1190·637	1088·732
	·196	4·9784	·03017193	19·465722	613·12	5·5738	172·8070	2·87059	5·78677	1·4632	·0008312	·0009090	1203·080	1100·110
	·197	5·0038	·03048059	19·664857	619·39	5·6308	174·5751	2·84153	5·72819	1·4484	·0008230	·0009000	1215·111	1111·111
	·198	5·0292	·03079082	19·865005	625·70	5·6882	176·3535	2·81287	5·67043	1·4338	·0008147	·0008910	1227·384	1122·334
	·199	5·0546	·03110263	20·066173	632·03	5·7457	178·1377	2·78470	5·61363	1·4194	·0008064	·0008819	1240·049	1133·915
	·200	5·0800	·03141600	20·268347	638·40	5·8036	179·9330	2·75691	5·55762	1·4053	·0007985	·0008732	1252·405	1145·213
	·201	5·1054	·03173095	20·471540	644·80	5·8618	181·7369	2·72955	5·50246	1·3915	·0007906	·0008646	1264·862	1156·604
	·202	5·1308	·03204746	20·675739	651·23	5·9203	183·5492	2·70260	5·44813	1·3777	·0007828	·0008561	1277·421	1168·088
6*	·203	5·1562	·03236555	20·880958	657·70	5·9791	185·3727	2·67602	5·39454	1·3642	·0007751	·0008477	1290·079	1179·662
	·204	5·1816	·03268521	21·087190	664·19	6·0381	187·2020	2·64086	5·34182	1·3508	·0007675	·0008393	1302·991	1191·469
	·205	5·2070	·03300644	21·294435	670·72	6·0975	189·0424	2·62407	5·28982	1·3377	·0007601	·0008312	1315·688	1203·080
	·206	5·2324	·03332923	21·502686	677·28	6·1571	190·8914	2·59865	5·23858	1·3247	·0007527	·0008232	1328·475	1214·772
	·207	5·2578	·03365361	21·711963	683·87	6·2170	192·7488	2·57361	5·18810	1·3120	·0007454	·0008152	1341·511	1226·693
	·208	5·2832	·03397955	21·922246	690·49	6·2772	194·6146	2·54894	5·13836	1·2994	·0007383	·0008074	1354·471	1238·543
	·209	5·3086	·03430706	22·133543	697·15	6·3377	196·4917	2·52458	5·08927	1·2870	·0007312	·0007996	1367·685	1250·626
	·210	5·3340	·03463614	22·345852	703·84	6·3985	198·3773	2·50059	5·04090	1·2747	·0007243	·0007921	1380·634	1262·467
5½*	·211	5·3594	·03496679	22·559174	710·55	6·4596	200·2685	2·47698	4·99330	1·2627	·0007174	·0007845	1394·009	1274·697
	·212	5·3848	·03529902	22·773516	717·31	6·5210	202·1738	2·45363	4·94624	1·2508	·0007107	·0007772	1407·102	1286·670
	·213	5·4102	·03563281	22·988864	724·09	6·5827	204·0848	2·43065	4·89992	1·2391	·0007040	·0007699	1420·443	1298·869

	·214	5·4356	·03596818	23·205231	730·91	6·6446	206·0070	2·40797	4·85420	1·2275	·0006975	·0007628	1433·666	1310 960
	·215	5·4610	·03630512	23·422611	737·75	6·7068	207·9348	2·38565	4·80920	1·2162	·0006910	·0007557	1447·135	1323 276
	·216	5·4864	·03664362	23·640998	744·63	6·7694	209·8740	2·36361	4·76476	1·2049	·0006846	·0007487	1460·665	1335·648
	·217	5·5118	·03698370	23·860404	751·54	6·8322	211·8216	2·34187	4·72095	1·1938	·0006783	·0007418	1474·252	1348 072
	·218	5 5372	·03732535	24·080823	758·49	6·8953	213·7804	2·32042	4·67770	1·1829	·0006721	·0007350	1487 891	1360·544
	·219	5·5626	·03766857	24·302255	765·46	6·9587	215·7449	2·29929	4·63510	1·1721	·0006660	·0007283	1501·580	1373·061
5^s	·220	5·5880	·03801336	24·524699	772·46	7 0224	217·7179	2·27845	4·59310	1·1615	·0006599	·0007217	1515·311	1385·617
	·221	5·6134	·03835972	24·748156	779·50	7·0864	219·7021	2·25788	4·55162	1·1510	·0006540	·0007152	1529·082	1398·210
	·222	5·6388	·03870765	24·972628	786·57	7·1507	221·6948	2·23758	4·51071	1·1407	·0006481	·0007088	1542·889	1410·835
	·223	5·6642	·03905716	25·198117	793·68	7·2152	223·6987	2·21754	4·47030	1·1305	·0006423	·0007024	1556·946	1423·689
	·224	5·6896	·03940823	25·424613	800·81	7·2801	225·7083	2·19779	4·43050	1·1204	·0006366	·0006962	1570·813	1436·369
	·225	5·7150	·03976088	25·652129	807·98	7·3452	227·7292	2·17829	4·39118	1·1104	·0006309	·0006900	1584·927	1449·275
	·226	5·7404	·04011509	25·880651	815·17	7.4106	229·7557	2·15908	4·35245	1·1006	·0006254	·0006839	1588·128	1452·202
	·227	5·7658	·04047088	26·110193	822·40	7·4764	231·7934	2·14010	4·31419	1·0910	·0006199	·0006779	1613·217	1475·144
	·228	5·7912	·04082823	26·340741	829·67	7·5424	233·8425	2·12134	4·27638	1·0814	·0006144	·0006719	1627·622	1488 316
$4\frac{1}{2}^s$	·229	5·8166	·04118716	26·572308	836·96	7·6087	235·8972	2·10287	4·23914	1·0720	·0006091	·0006661	1641·795	1501·276
	·230	5·8420	·04154766	26·804888	844·29	7·6753	237·9631	2·08461	4·20233	1·0627	·0006038	·0006603	1656·217	1514·463
	·231	5 8674	·04190973	27·038481	851·64	7·7422	240·0347	2·06662	4·16607	1·0535	·0005986	·0006546	1670·638	1527·650
	·232	5·8928	·04227337	27·273087	859·03	7·8094	242·1176	2·04884	4·13022	1 0444	·0005934	·0006489	1685·314	1541·070
	·233	5·9182	·04263858	27·508706	866·45	7·8768	244·2089	2·03129	4·09485	1·0355	·0005883	·0006434	1699·720	1554·243
	·234	5·9436	·04300536	27·745338	873·91	7·9446	246·3115	2·01395	4·05990	1·0267	·0005833	·0006379	1714·375	1567·644
	·235	5·9690	·04337372	27·982989	881·39	8·0127	248·4198	1·99686	4 02544	1·0179	·0005784	·0006325	1729·012	1581·028
	·236	5·9944	·04374364	28·221647	888 91	8·0810	250·5393	1·97997	3·99139	1·0093	·0005735	·0006272	1743·623	1594·388
	·237	6·0198	·04411513	28·461317	896·46	8·1496	252·6673	1·96330	3·95778	1·0008	·0005687	·0006219	1758·483	1607·976
4^s	·238	6·0452	·04448820	28·702007	904·04	8·2185	254·8037	1·94683	3·92459	·99245	·0005639	·0006167	1773·310	1621·534
	·239	6·0706	·04486283	28·943703	911·65	8·2877	256·9486	1·93058	3·89183	·98416	·0005592	·0006115	1788·389	1635·323
	·240	6·0960	·04523904	29·186419	919·30	8·3572	259·1047	1·91451	3 85944	·97598	·0005545	·0006064	1803 431	1649·077
	·241	6·1214	·04561682	29·430148	926·97	8·4270	261·267	1·8987	3·8275	·96790	·0005499	·00060137	1818·514	1662·870
	·242	6·1468	·04599617	29·674889	934·68	8·4971	263·460	1·8830	3·7959	·95991	·0005454	·00059645	1833·515	1676·587
	·243	6·1722	·04637708	29·920637	942·42	8·5675	265·621	1·8676	3·7648	·95203	·0005409	00059153	1848·765	1690·531
	·244	6·1976	·04675957	30·167404	950·20	8·6381	267·814	1·8522	3·7339	·94424	·0005365	·00058672	1863·922	1704·391
	·245	6·2230	·04714364	30·415191	958·00	8·7091	270 012	1·8372	3·7035	·93655	·0005321	·00058191	1879·328	1718·479
	·246	6·2484	·04752927	30·663984	965·84	8·7803	272·222	1·8223	3·6735	·92895	·0005278	·00057720	1896·664	1732·502
	·247	6 2738	·04791647	30·913790	973·70	8·8519	274·437	1·8075	3·6438	·92144	·0005235	·00057250	1910·218	1746·725
$3\frac{1}{2}^s$	·248	6·2992	·04830524	31 164609	981·61	8·9237	276·667	1·7930	3·6145	·91403	·0005193	·00056791	1925·657	1760·842
	·249	6·3246	·04869559	31·416447	989·53	8·9958	278·899	1·7787	3·5856	·90670	·0005152	·00056342	1941·003	1774·875
	·250	6·3500	·04908750	31·669292	997·04	9·0640	281·016	1·7652	3·5585	·89946	·0005111	·00055894	1956·561	1789·101

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Diameter		Section		Weight per length.			Length per weight.		Resistance of Pure Copper at 75° F.				
										Ohms per length.			Length per Ohm.	
Nearest B.W. Gauge.	in Inches.	in Milli-Metres.	in Square Inches.	in Square Millimetres.	lbs. per 1760 yds.	ounces per yard.	grammes per metre or kilo-grammes per kilo-metre.	Yards per pound.	Metres per kilo-gramme.	Ohms per 1760 yds.	Ohms per yard.	Ohms per metre.	Yards.	Metres.
	·190	4·8260	·02835294	18·292183	576·16	5·2378	162·3907	3·05473	6·15799	1·5571	·0008849	·0009677	1130·102	1033·378
6½s	·191	4·8514	·02865218	18·485241	582·24	5·2931	164·1043	3·02283	6·09368	1·5408	·0008755	·0009575	1142·140	1044·386
	·192	4·8768	·02895299	18·679311	588·35	5·3486	165·8264	2·99144	6·03040	1·5248	·0008665	·0009476	1154·074	1055·298
	·193	4·9022	·02925537	18·874395	594·49	5·4045	167·5570	2·96055	5·96812	1·5091	·0008575	·0009378	1166·133	1066·325
	·194	4·9276	·02955931	19·070485	600·67	5·4606	169·2988	2 93009	5·90672	1·4936	·0008485	·0009279	1178·575	1077·702
	·195	4·9530	·02986484	19·267600	606 88	5·5171	171·0491	2·90010	5·84627	1·4783	·0008399	·0009185	1190·637	1088·732
	·196	4 9784	·03017193	19·465722	613·12	5·5738	172·8079	2·87059	5 78677	1·4632	·0008312	·0009090	1203·080	1100·110
	·197	5·0038	·03048059	19·664857	619·39	5·6308	174·5751	2·84153	5·72819	1·4484	·0008230	·0009000	1215·111	1111·111
	·198	5·0292	·03079082	19·865005	625·70	5 6882	176·3535	2·81287	5·67043	1·4338	·0008147	·0008910	1227·384	1122·334
	·199	5 0546	·03110263	20·066173	632·03	5·7457	178·1377	2·78470	5·61363	1·4194	·0008064	·0008819	1240·049	1133·915
	·200	5·0800	·03141600	20·268347	638·40	5 8036	179·9330	2·75691	5·55762	1·4053	·0007985	·0008732	1252·405	1145·213
	·201	5·1054	·03173095	20·471540	644·80	5·8618	181·7369	2·72955	5·50246	1·3915	·0007906	·0008646	1264·862	1156·604
	·202	5·1308	·03204746	20 675739	651·23	5·9203	183·5492	2·70260	5·44813	1·3777	·0007828	·0008561	1277·421	1168·088
6s	·203	5·1562	·03236555	20·880958	657·70	5·9791	185·3727	2·67602	5·39454	1·3642	·0007751	·0008477	1290 079	1179·662
	·204	5·1816	·03268521	21·087190	664·19	6·0381	187·2020	2·64986	5·34182	1·3508	·0007675	·0008393	1302·991	1191·460
	·205	5·2070	·03300644	21·294435	670·72	6·0975	189·0424	2·62407	5·28982	1·3377	·0007601	·0008312	1315·688	1203·060
	·206	5·2324	·03332923	21·502686	677·28	6·1571	190·8914	2·59865	5·23858	1·3247	·0007527	·0008232	1328·475	1214·772
	·207	5·2578	·03365361	21·711963	683·87	6·2170	192·7488	2·57361	5·18810	1·3120	·0007454	·0008152	1341·511	1226·693
	·208	5·2832	·03397955	21·922246	690·49	6·2772	194·6146	2·54894	5·13836	1·2994	·0007383	·0008074	1354·471	1238·543
	·209	5·3086	·03430706	22·133543	697·15	6·3377	196·4917	2·52458	5·08927	1·2870	·0007312	·0007996	1367·685	1250·626
	·210	5·3340	·03463614	22·345852	703·84	6·3985	198·3773	2·50059	5·04090	1·2747	·0007243	·0007921	1380·634	1262·467
5½s	·211	5·3594	·03496679	22·559174	710·55	6·4596	200·2685	2·47698	4·99330	1·2627	·0007174	·0007845	1394 009	1274·697
	·212	5·3848	·03529902	22·773516	717·81	6·5210	202·1738	2·45863	4·94624	1·2508	·0007107	·0007772	1407·102	1286·670
	·213	5·4102	·03563281	22·988864	724·09	6·5827	204·0848	2.43065	4·89992	1·2391	·0007040	·0007699	1420·443	1298·869

AREAS OF CIRCLES, ADVANCING BY 10THS.

Diam.	Areas.										Diam.
	·0	·1	·2	·3	·4	·5	·6	·7	·8	·9	
0	·0	·0078	·0314	·0706	·1256	·1963	·2827	·3848	·5026	·6361	0
1	·7854	·9503	1·1309	1·3273	1·5393	1·7671	2·0106	2·2698	2·5446	2·8352	1
2	3·1416	3·4636	3·8013	4·1547	4·5239	4·9087	5·3093	5·7255	6·1575	6·6052	2
3	7·0686	7·5476	8·0424	8·5530	9·0792	9·6211	10·1787	10·7521	11·3411	11·9559	3
4	12·5664	13·2025	13·8544	14·5220	15·2053	15·9043	16·6190	17·3494	18·0951	18·8574	4
5	19·6350	20·4282	21·2372	22·0618	22·9022	23·7583	24·6301	25·5176	26·4208	27·3397	5
6	28·2744	29·2247	30·1907	31·1725	32·1699	33·1831	34·2120	35·2566	36·3168	37·3928	6
7	38·4846	39·5920	40·7151	41·8539	43·0085	44·1787	45·3647	46·5663	47·7837	49·0168	7
8	50·2656	51·5300	52·8102	54·1062	55·4178	56·7451	58·0881	59·4469	60·8213	62·2115	8
9	63·6174	65·0389	66·4762	67·9292	69·3979	70·8823	72·3824	73·8982	75·4298	76·9770	9
10	78·5400	80·1186	81·7130	83·3230	84·9488	86·5903	88·2475	89·9204	91·6090	93.3133	10
11	95·0334	96·7691	98·5205	100·287	102·070	103·869	105·683	107·513	109.359	111·220	11
12	113·097	114·990	116·898	118·823	120·763	122·718	124·690	126·677	128·679	130·698	12
13	132·732	134·782	136·848	138·929	141·026	143·139	145·267	147·411	149·571	151·747	13
14	153·938	156·145	158·368	160·606	162·860	165·130	167·415	169·717	172·034	174·366	14
15	176·715	179·079	181·458	183·854	186·265	188·692	191·134	193·593	196·067	198·556	15
16	201·062	203·583	206·120	208·672	211·241	213·825	216·424	219·040	221·671	224·318	16
17	226·980	229·658	232·352	235·062	237·787	240·528	243·285	246·057	248·846	251·650	17
18	254·469	257·304	260·155	263·022	265·905	268·803	271·716	274·646	277·591	280·552	18
19	283·529	286·521	289·529	292 553	295·593	298·648	301·719	304·805	307·908	311·026	19
20	314·160	317·309	320·474	323·655	326·852	330·064	333·292	336·536	339·795	343·070	20
	·0	·1	·2	·3	·4	·5	·6	·7	·8	·9	

AREAS OF CIRCLES, ADVANCING BY 10THS—*Continued.*

Diam.	Areas.										Diam.
	·0	·1	·2	·3	·4	·5	·6	·7	·8	·9	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	359·681	363·051	366·436	369·837	373·253	376·685	21
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	394·082	397·608	401·150	404·708	408·282	411·871	22
[illegible]	[illegible]	[illegible]	422·733	426·385	430·053	433·737	437·436	441·151	444·881	448·628	23
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	471·436	475·292	479·164	483·052	486·955	24
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	506·708	510·706	514·719	518·748	522·793	526·854	25
[illegible]	[illegible]	[illegible]	[illegible]	543·253	547·392	551·547	555·717	559·903	564·105	568·323	26
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	589·646	593·958	598·286	602·629	606·988	611·363	27
[illegible]	[illegible]	[illegible]	624·581	629·010	633·472	637·941	642·425	646·926	651·442	655·973	28
[illegible]	[illegible]	[illegible]	[illegible]	674·258	678·868	683·494	688·136	692·793	697·466	702·155	29
[illegible]	[illegible]	[illegible]	716·816	721·067	725·835	730·618	735·417	740·231	745·061	749·907	30
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	774·372	779·313	784·268	789·240	794·227	799·230	31
[illegible]	[illegible]	[illegible]	814·384	[illegible]	824·481	829·578	834·691	839·820	844·964	850·124	32
[illegible]	[illegible]	[illegible]	[illegible]	870·922	876·160	881·458	886·685	891·970	897·272	902·589	33
[illegible]	[illegible]	918·270	[illegible]	924·011	929·410	934·822	940·249	945·692	951·150	956·625	34
[illegible]	[illegible]	[illegible]	973·142	978·679	984·231	989·800	995·384	1000·98	1006·60	1012·23	35
[illegible]	1017·87	1023·54	1029·21	1034·91	1040·62	1046·34	1052·09	1057·84	1063·62	1069·40	36
[illegible]	1075·21	1081·03	1086·86	1092·71	1098·58	1104·46	1110·36	1116·28	1122·21	1128·15	37
[illegible]	1134·11	1140·09	1146·08	1152·09	1158·11	1164·15	1170·21	1176·28	1182·37	1188·41	38
[illegible]	1194·59	1200·72	1206·87	1213·04	1219·22	1225·42	1231·63	1237·86	1244·10	1250·36	39
40	1256·04	1262·93	1269·23	1275·56	1281·89	1288·25	1294·62	1301·00	1307·40	1313·82	40
	·0	·1	·2	·3	·4	·5	·6	·7	·8	·9	

AREAS OF CIRCLES, ADVANCING BY 10THS—*Continued.*

Diam.	Areas.										Diam.
	·0	·1	·2	·3	·4	·5	·6	·7	·8	·9	
41	1320·25	1326·70	1333·16	1339·64	1346·14	1352·65	1359·18	1365·72	1372·28	1378·85	41
42	1385·44	1392·05	1398·67	1405·30	1411·96	1418·62	1425·31	1432.01	1438·72	1445·45	42
43	1452·20	1458·96	1465·74	1472·53	1479·34	1486·17	1493·01	1499·87	1506·74	1513·62	43
44	1520·53	1527·45	1534·38	1541·33	1548·30	1555·28	1562·28	1569·29	1576·32	1583·37	44
45	1590·43	1597·51	1604·60	1611·71	1618 83	1625·97	1633·12	1640·30	1647·48	1654·68	45
46	1661·90	1669·13	1676·38	1683·65	1690·93	1698·23	1705.54	1712·87	1720·21	1727·57	46
47	1734·94	1742·33	1749·74	1757·16	1764·60	1772·05	1779·52	1787·01	1794·51	1802·02	47
48	1809·56	1817·10	1824·67	1832·25	1839·84	1847·45	1855·08	1862·72	1870·38	1878·05	48
49	1885·74	1893·45	1901·17	1908·90	1916·65	1924·42	1932·20	1940·00	1947·82	1955·65	49
50	1963·50	1971·36	1979·23	1987·13	1995·04	2002·96	2010·90	2018·86	2026·83	2034·82	50
51	2042·82	2050·84	2058·87	2066·92	2074·99	2083·07	2091·17	2099·28	2107·41	2115·56	51
52	2123·72	2131·89	2140·08	2148·29	2156·51	2164·75	2173·01	2181·28	2189·56	2197·87	52
53	2206·18	2214·52	2222·87	2231·23	2239·61	2248·01	2256·42	2264·85	2273·29	2281·75	53
54	2290·22	2298·71	2307·22	2315·74	2324·28	2332·83	2341·40	2349·98	2358·58	2367·20	54
55	2375·83	2384·48	2393·14	2401·82	2410·51	2419·22	2427·95	2436·69	2445·45	2454·22	55
56	2463·01	2471·81	2480·63	2489·47	2498·32	2507·19	2516·07	2524·97	2533·88	2542·81	56
57	2551·76	2560·72	2569·70	2578·69	2587·70	2596·72	2605·76	2614·12	2623·89	2632·98	57
58	2642·08	2651·20	2660·33	2669·48	2678·65	2687·83	2697·03	2706·24	2715·47	2724·71	58
59	2733·97	2743·25	2752·54	2761·85	2771·17	2780·51	2789·86	2799·23	2808·62	2818·02	59
60	2827·44	2836·87	2846·32	2855·78	2865·26	2874·76	2884·26	2893·79	2903·34	2912·89	60
	·0	·1	·2	·3	·4	·5	·6	·7	·8	·9	

AREAS OF CIRCLES, ADVANCING BY 10THS—*Continued.*

Diam.	Areas.										Diam.
	·0	·1	·2	·3	·4	·5	·6	·7	·8	·9	
21	346·361	349·667	352·990	356·328	359·681	363·051	366·436	369·837	373·253	376·685	21
22	380·133	383·597	387·076	390·571	394·082	397·608	401·150	404·708	408·282	411·871	22
23	415·476	419·097	422·733	426·385	430·053	433·737	437·436	441·151	444·881	448·628	23
24	452·390	456·168	459·961	463·770	467·595	471·436	475·292	479·164	483·052	486·955	24
25	490·875	494·809	498·760	502·726	506·708	510·706	514·719	518·748	522·793	526·854	25
26	530·930	535·022	539·129	543·253	547·392	551·547	555·717	559·903	564·105	568·323	26
27	572·556	576·805	581·070	585·350	589·646	593·958	598·286	602·629	606·988	611·363	27
28	615·753	620·159	624·581	629·019	633·472	637·941	642·425	646·926	651·442	655·973	28
29	660·521	665·084	669·663	674·258	678·868	683·494	688·136	692·793	697·466	702·155	29
30	706·860	711·580	716·316	721·067	725·835	730·618	735·417	740·231	745·061	749·907	30
31	754·769	759·646	764·539	769·448	774·372	779·313	784·268	789·240	794·227	799·230	31
32	804·249	809·284	814·334	819·399	824·481	829·578	834·691	839·820	844·964	850·124	32
33	855·300	860·492	865·699	870·922	876·160	881·458	886·685	891·970	897·272	902·589	33
34	907·922	913·270	918·635	924·011	929·410	934·822	940·249	945·692	951·150	956·625	34
35	962·115	967·620	973·142	978·679	984·231	989·800	995·384	1000·98	1006·60	1012·23	35
36	1017·87	1023·54	1029·21	1034·91	1040·62	1046·34	1052·09	1057·84	1063·62	1069·40	36
37	1075·21	1081·03	1086·86	1092·71	1098·58	1104·46	1110·36	1116·28	1122·21	1128·15	37
38	1134·11	1140·09	1146·08	1152·09	1158·11	1164·15	1170·21	1176·28	1182·37	1188·41	38
39	1194·59	1200·72	1206·87	1213·04	1219·22	1225·42	1231·63	1237·86	1244·10	1250·36	39
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STRENGTH AND WEIGHT OF METALS.

	Specific Gravity.	Weight of a cubic foot.	Weight of a cubic inch.	Tensile Strength per sq. in.	Crushing Weight per sq. in.	Transverse Strength.
		lbs.	lbs.	tons.	tons.	tons.
Aluminium, sheet ..	2·67	166·6	·096	—	—	—
„ „ cast ..	2·56	159·8	·092	—	—	—
Antimony, cast ..	6·72	419·5	·242	·47	—	—
Bismuth, cast ..	9·822	613·1	·353	1·45	—	—
Copper bolts	8·85	552·4	·318	17	—	—
„ cast	8·607	537·3	·31	8·4	—	—
„ sheet	8·78	548·1	·316	13·4	—	—
„ wire	8·9	555	·32	26	—	—
Gold	19·361	1208·5	·697	9·1	—	—
Iron, cast, from ..	7	437	·252	6	36	2
„ „ to	7·6	474·4	·273	13	64	3·4
„ „ average .	7·23	451	·26	7·3	48	2·6
„ wrought, from	7·6	474·4	·273	16	16	3
„ „ to ..	7·8	486·9	·281	29	18	5·5
„ „ average	7·78	485·6	·28	22	16·9	3·8
„ wire	—	—	—	40	—	—
Lead, cast	11·36	708·5	·408	·8	3·1	—
„ sheet	11·4	711·6	·41	1·5	—	—
Mercury	13·596	848·75	·48945	—	—	—
Platinum	21·531	1343·9	·775	—	—	—
„ sheet ..	23	1435·6	·828	—	—	—
Silver	10·474	653·8	·377	18·2	—	—
Steel	8	499	·288	52	150	—
„ plates	—	—	—	35	90	—
Tin, cast	7·291	455·1	·262	2·0	6·7	—
Zinc, cast	7	437	·252	3·3	—	—

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